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A High Performance 45 MHz IF Amplifier for an Up-Conversion HF/LF Receiver

The author describes the design process for a high performance IF Amplifier.

The July/August 2013 edition of *QEX* contained an article about the design of the HF7070 up-conversion HF/LF receiver, which has a 45 MHz first IF. A key building block in this receiver was the IF amplifier, which was a 45 MHz version of the amplifier that uses four J310 junction FETs with source/gate feedback, originally designed by Bill Carver, W7AAZ, for use with down conversion receivers. At 45 MHz, it has a noise figure of 1.3 dB, a gain of 10 dB, a third order intercept point (IP3) output of 40 dBm, and a nominal 50 Ω input and output impedance. In the HF7070 *QEX* article, Table 1 showed the use of this amplifier in the signal path. The gain distribution in the IF strip was such that from a linearity point of view nothing was pushed to the limit.

In the HF7070 there is no preamplifier before the first H-Mode mixer, so it is essential that the first IF amplifier has a low noise figure and a high output IP3 in order to have a sensitive receiver that is also highly linear for close-in signals. It would have simplified the circuitry if an MMIC could have been used in place of the 4 × J310 amplifier, but at the time none were available with the performance of the 4 × J310 amplifier. A low noise figure and a high output IP3 were two conflicting requirements in the available MMICs. However recently Mini-Circuits have introduced the PHA-1+ and the dual matched version the PHA-11+. Unlike most MMICs designed for microwave applications the noise figure and IP3 out are at their best between 40 and 100 MHz, making them suitable for use as IF amplifiers in up-conversion receivers.

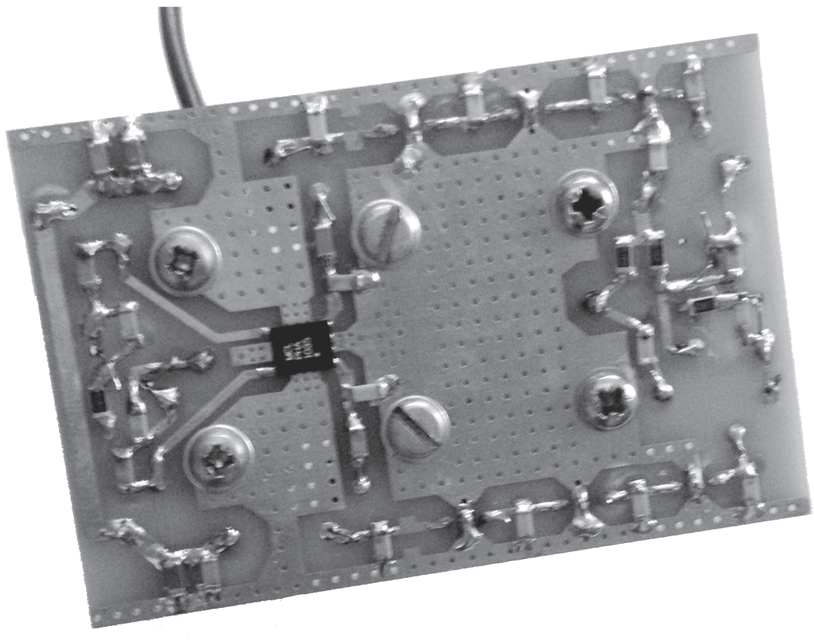


Photo A — Here is the circuit board/wiring side or the completed 45 MHz IF amplifier. The PHA-11 MMIC amplifier IC is to the left of center, near the RF output side of the amplifier. The wire connecting to the top of the board is the 5 V supply.

Unlike the 4 × J310 amplifier, however, the PHA-1+ has too much gain to drop it into the existing HF7070 IF strip. In addition its reverse isolation is not adequate for the output to directly drive a crystal filter like the 4 × J310 amplifier. This deficiency can be overcome by following the PHA-1+ with an 8 dB attenuator before the 4 pole crystal filter to smooth any reactance from the crystal filter and also make the PHA-1 output impedance nearer 50 Ω for the L match to the crystal filter. Fitting the 8 dB attenuator raises the input in-band IP3 of the crystal filter (26 dBm) to 34 dbm. This is still

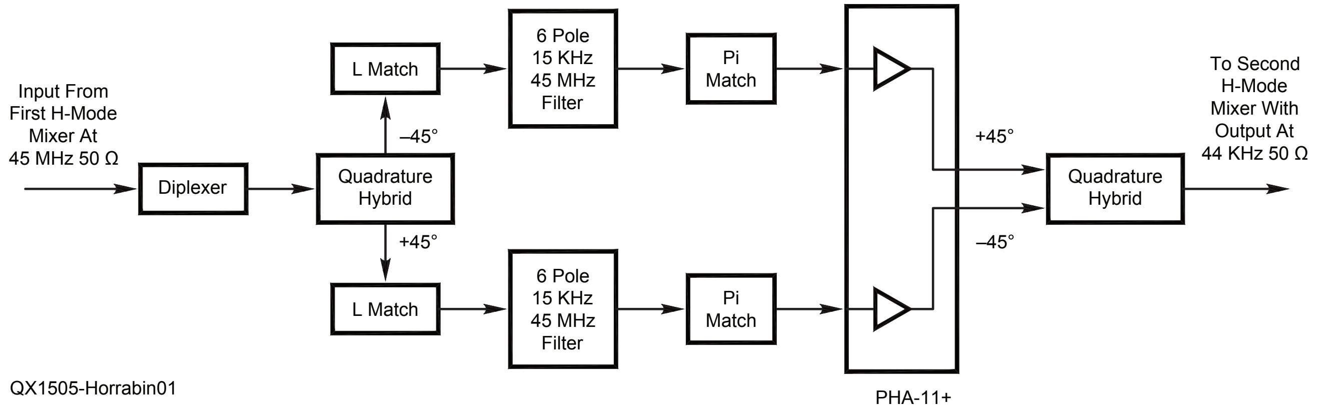


Figure 1 — This block diagram shows the improved architecture for the HF7070 45 MHz IF amplifier, using the PHA-11 MMIC. Note that it is necessary to have at least 110 dB of stop band attenuation at the second mixer image frequency. The 6 pole filter is made from three discrete 2 pole filters.

well below the PHA-1 output IP3 of 42 dBm.

To see if the PHA-1+ would be suitable in a practical design Dave Roberts, G8KBB, first measured its input impedance at 45 MHz using his N2PK vector network analyser (VNA). It was 80 Ω in parallel with 25 pF. Dave then measured the noise figure (NF) at 45 MHz from a 50 Ω source impedance, which was 2.2 dB. In one proposed use of this chip it would see an 80 Ω source impedance, so an L match was fitted to match its 80 Ω plus 25 pF input impedance to 50 Ω. When the chip saw an 80 Ω source impedance its NF was raised from 2.2 to 2.7 dB, which is quite a bit higher than the 1.3 dB of the 4 × J310 amplifier. The PHA-1+ has a gain at 45 MHz of 18 dB, however, and the higher gain could reduce the NF contribution from following stages.

In the present HF7070 45 MHz IF design the optimum gain block at 45 MHz is 20 dB and this is made up of two 4 × J310 amplifiers separated by a 4 pole roofing filter. Also the in-band IP3 of the receiver is ultimately determined by the in-band IP3 of the 4 pole crystal roofing filter that follows the first 4 × J310 amplifier. The 15 kHz bandwidth roofing filters at 45 MHz need to have six poles to get at least 110 dB attenuation at the second H-Mode mixer image frequency. In the existing design there are two poles of quadrature hybrid connected 45 MHz, 15 kHz bandwidth crystal filters after the first mixer. There is then a 4 × J310 amplifier and then a 4 pole filter followed by another 4 × J310 amplifier and then the second H-Mode mixer, to give a 44 kHz output frequency for the 25 bit audio ADC.

Because the PHA-1+ has 18 dB gain, a different IF architecture offered a simplification of the circuit and the possibility of a significant improvement of in-band IP3 and a better out of band IP3 at 20 kHz spacing. See Figure 1. The penalty would be a 2 dB increase in receiver noise figure. If necessary, a preamplifier for use above 7 MHz could be used, based on the push pull MRF 581A amplifier originally designed by Jacob Makhinson, N6NWP, that was presented in *QST*. The MRF 581A is still available, and an 8.8 dB gain with a noise figure of 2.5 dB and an IP3 out of 57 dBm should be possible. The use of this amplifier would not significantly affect the receiver dynamic range, and it would only really be needed to provide extra sensitivity of the receiver for reception of signals above 7 MHz.

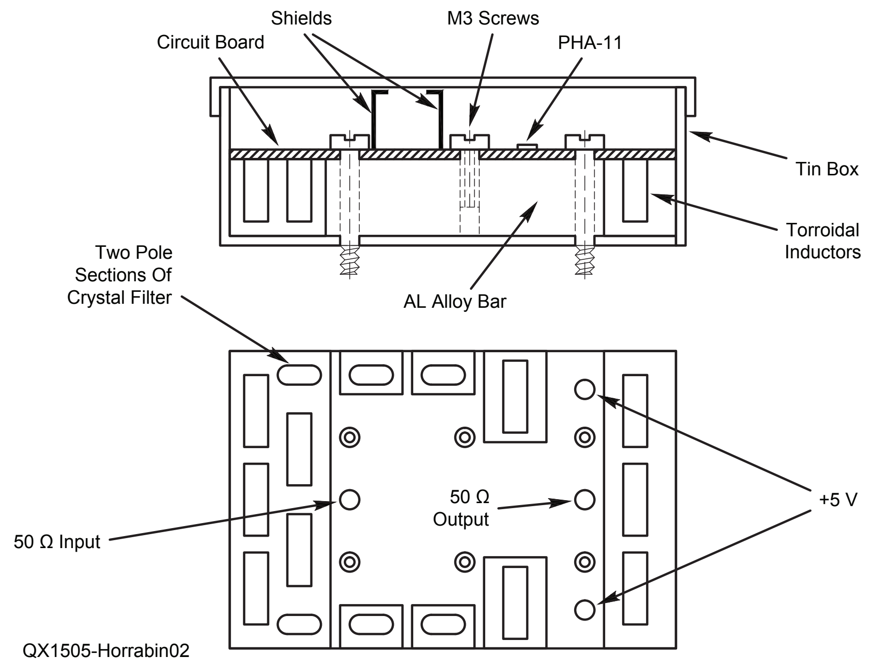
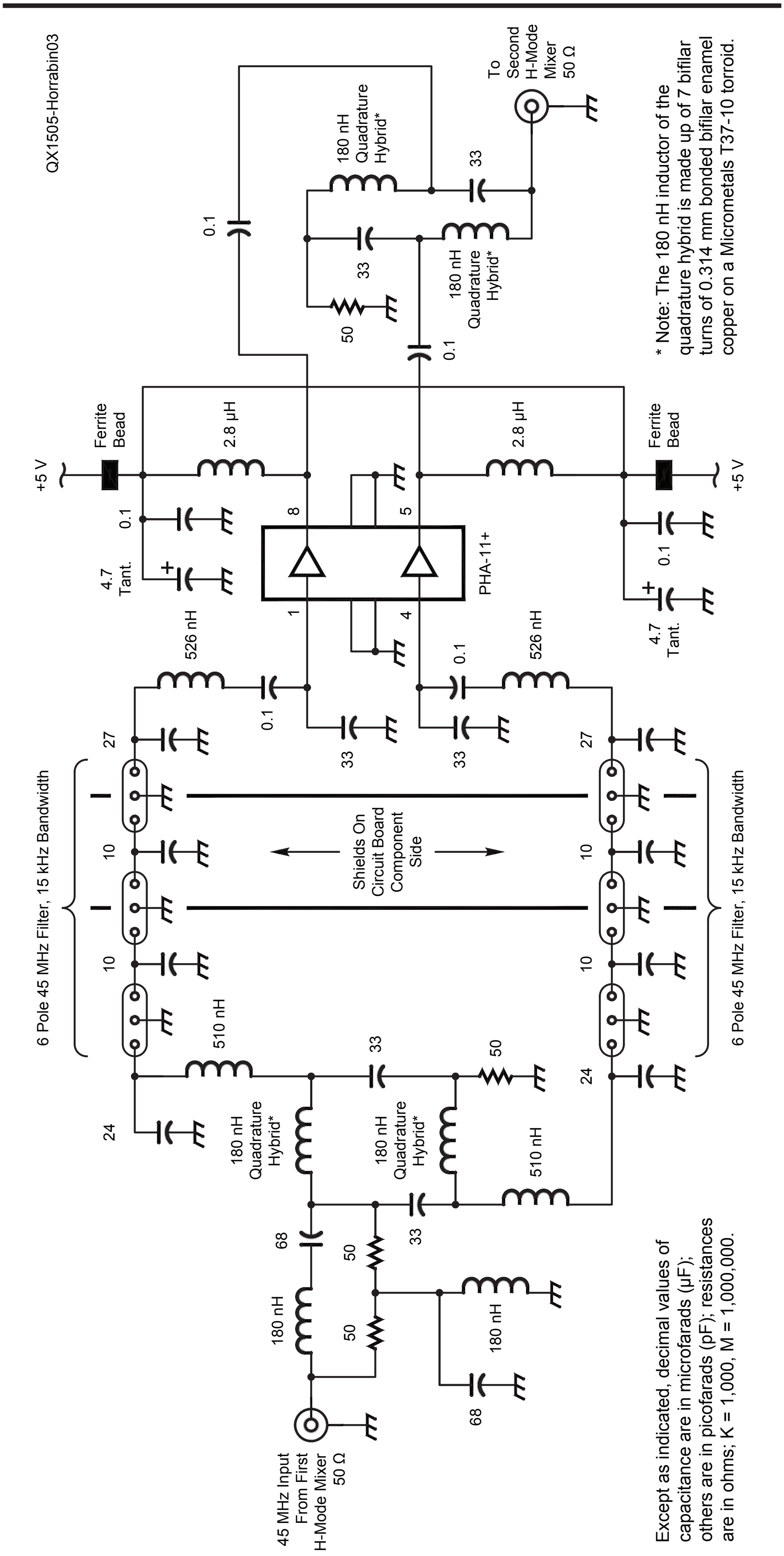


Figure 2 — This diagram shows the mechanical details of the PHA-11 amplifier.

In the new IF architecture described using the PHA-11+ MMIC, all six poles of roofing filter are in one place so that careful shielding from input to output is needed. See Figure 2. This has been achieved by machining a 12 mm thick piece of aluminium bar fitted inside a tin box of dimensions 50 × 75 × 25 mm. The aluminium bar also doubles as a heat sink to the PHA-11+ MMIC used in the design, which is the dual matched version of the PHA-1+. One of my neighbors, Alan Heywood — whose brother is a radio



amateur — builds model steam engines for a hobby, and has a good mechanical workshop. He offered to do all the mechanical work. The circuit shown in Figure 3 was constructed on a commercially made, double sided circuit board with plated through holes. Figure 4 shows the circuit board pattern. The circuit board has thermal vias to conduct heat from the chip to the aluminium bar. It was essential to keep the chip temperature down to get the best noise figure and with a dissipation of about 1.25 W, the chip temperature was only 34°C.

All of the inductors in the unit were wound on T37-10 powdered iron torriods because it was convenient to do so for the prototype. In a commercial design, surface mount inductors could be used to replace all the torriods, except for the two that form part of a quadrature hybrid. In the HF7070 radio most of the RF inductors were surface mount shielded chokes manufactured by Vishay.

Construction

I designed the circuit of the 45 MHz amplifier, the circuit board layout, and also drew up the mechanical side of the job. The commercially made printed circuit boards were made by Fischer in Germany. George Fare, G3OGQ, used a software circuit board design package to generate the necessary files for commercial manufacture from my free-hand graph paper layout. Martein Bakker, PA3AKE, arranged the manufacture of the circuit boards with the German company, and also paid for them as his personal contribution to this project.

A few PHA-11+ MMICs were supplied by John-Paul Newbold of Mini-Circuits Europe and two of these chips were reflow soldered onto the commercially made circuit boards in the electronics workshop at Daresbury Laboratory. The mechanical drawing of Figure 2 shows that the circuit board is secured to the aluminium bar by six M3 screws. The outer four screws project from the base of the tin box, so that the completed IF strip could be mounted to a motherboard. Before any of the passive components were soldered to the circuit board, the board was loosely screwed to the machined aluminium bar and this was placed into the tin box to see if there were any tolerance issues. There wasn't, so the six M3 screws were fully tightened, securing the circuit board to the aluminium block. The circuit board and aluminium block were then

Figure 3 — This schematic diagram shows the 45 MHz IF amplifier circuit. Note that the 180 nH inductor of the quadrature hybrid is made with 7 bifilar turns of 0.314 mm bonded bifilar enamel copper wire on a Micrometals T37-10 powdered iron toroid.

gripped in a small vice so that the surface mount capacitors and 50 Ω resistors could be fitted. Unlike George and Dave, I had never done any serious surface mount assembly before, but by using a special pair of tweezers I found it easy to do (or as we British would say "A piece of cake").

All of the inductors in the design were wound on Micrometals T37–10 toroids. What made the winding of the toroids easy to do was the use of the capacitance and inductance measuring box from Almost All Digital Electronics USA (**www.aade.com**). The result was that the first time the amplifier was switched on it worked straight away and only minor adjustments were needed to remove a 1 dB dip in the passband. After the initial performance tests the edges of the circuit board were soldered to the tin box and two internal shields were fitted to improve the stop band of the unit at 45 MHz minus 90 kHz, the second H-mode mixer image frequency.

Performance Tests

The design team met at Dave Roberts' house one evening with the prototype 45 MHz IF amplifier. Although the unit was designed to mount on a motherboard, two SMA sockets were fitted to the unit for testing, and a shield fitted between them. Using an N2PK vector network analyzer (VNA), its transmission characteristics were plotted. See the graphs of Figure 5. Also the circuit noise figure (NF) and gain were measured using Dave's NF measuring gear. See Figure 6.

The noise figure was measured as 6 dB, and this was what it should be, remembering that the insertion loss of the 6 pole crystal filter forms part of this circuit and should account for about 3.5 dB. Overall circuit gain was 14 dB. What was disappointing was that the stop band was only 80 dB, although at that point the internal shields had not yet been fitted. It was nowhere near the 110 dB desired, however. Two internal shields were then fitted inside the tin box and its transmission characteristics measured again. See Figure 7. The stop band was improved by around 20 dB, but some more work is needed to further improve this.

Next, I visited the RF lab at Daresbury Laboratory to measure the in-band and out of band IP3 of the circuit. Two visits were required due to problems with the first set of measurements. I discussed the first set of results with Martein Bakker, PA3AKE, and set out the next time with a definite strategy in mind. The next IP3 results are shown in Table 1. The big surprise has been the significant improvement in out of band IP3.

The two amplifiers in the PHA-11 have their outputs summed by the second

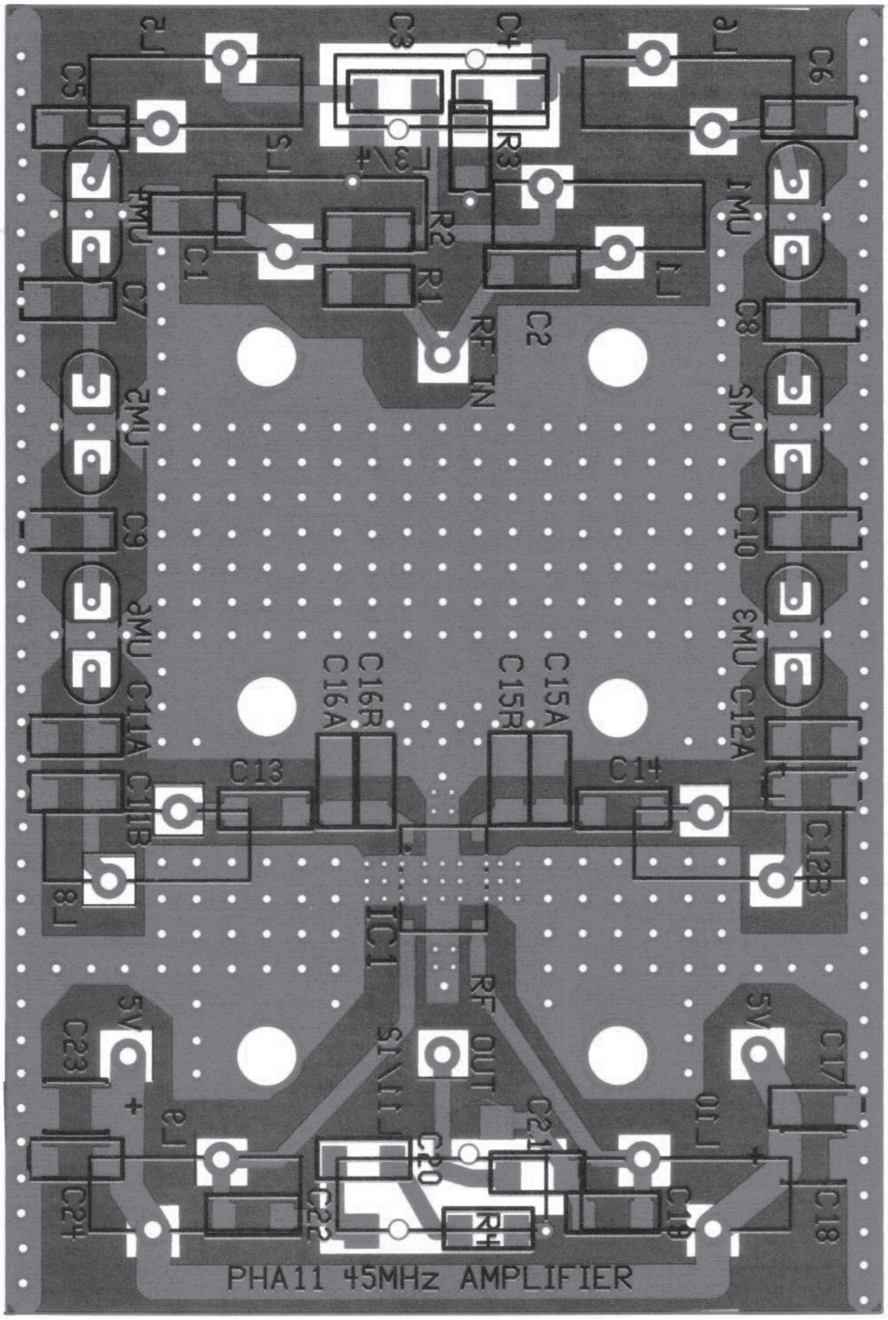
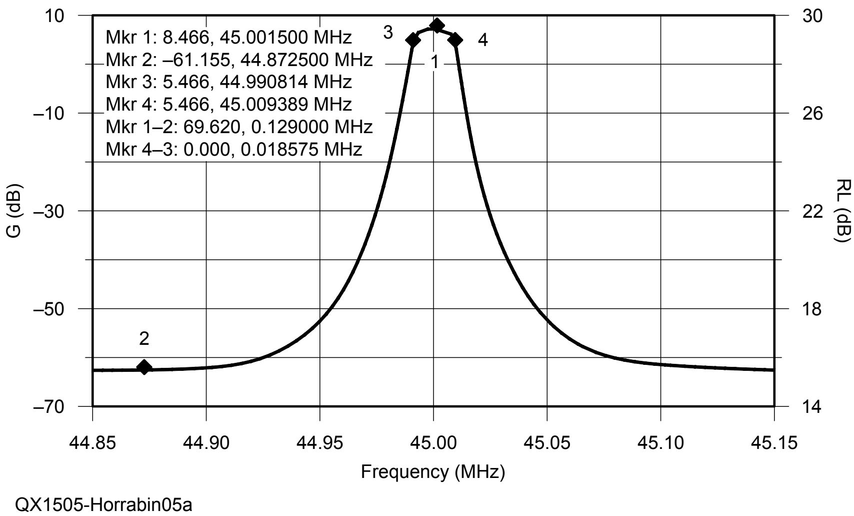


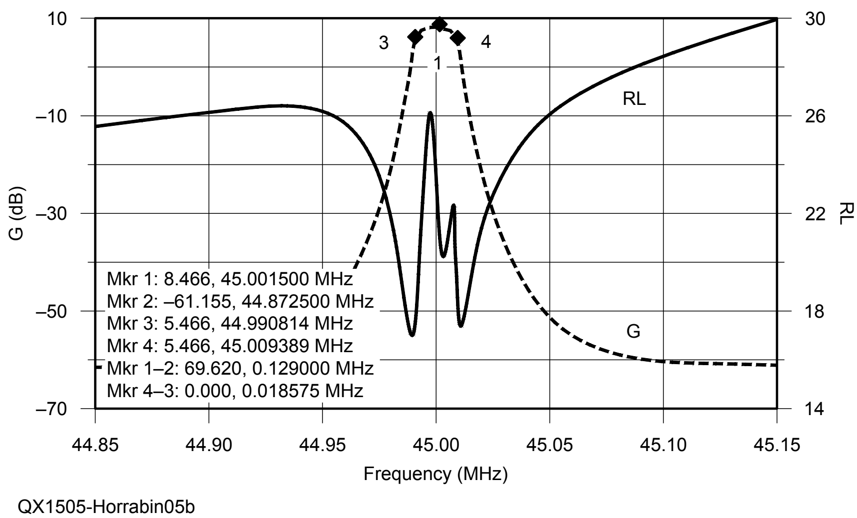
Figure 4 — Here is the circuit board etching pattern for the 45 MHz IF amplifier. This is not to scale. The actual circuit board files are available for download from the ARRL QEX files website. Go to www.arrl.org/qexfiles and look for the file 5x15_Horrabin.zip.

Table 1
Measured Performance of the IF Amplifier

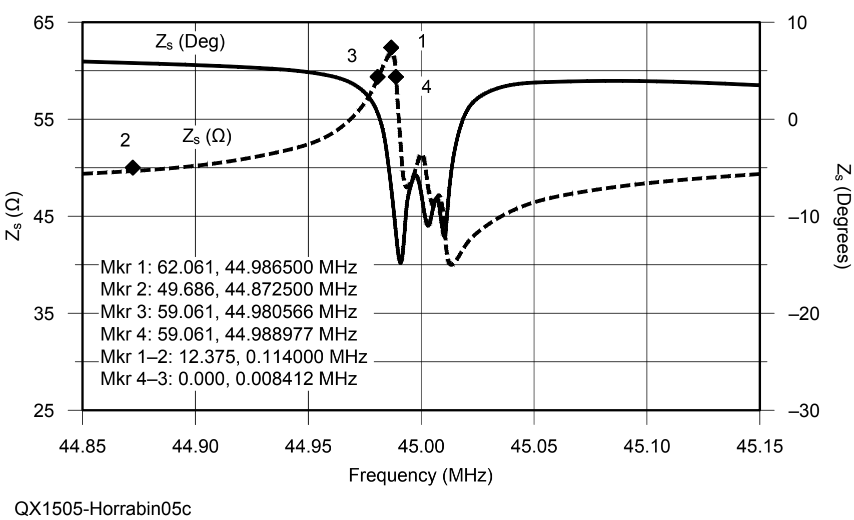
Test Tone (kHz)	*IP3 Product (dBm)*	*Output IP3 (dBm)*	*Input Ip3 (dBm)*	*RX IP3 (dBm)*
2	–75	37.5	23.5	30.5
5	–96	48	34	41
10	–92 (–75)	46 (52.5)	32 (38.5)	39 (45.5)
20	–126 (–89)	63 (59.5)	49 (45.5)	56 (52.5)
40	–130 (–98)	65 (64)	51 (50)	58 (57)
80	–115	57.5	43.5	50.5


Mkr 1: 8.466, 45.001500 MHz
Mkr 2: –61.155, 44.872500 MHz
Mkr 3: 5.466, 44.990814 MHz
Mkr 4: 5.466, 45.009389 MHz
Mkr 1–2: 69.620, 0.129000 MHz
Mkr 4–3: 0.000, 0.018575 MHz
G (dB)
RL (dB)
Frequency (MHz)
QX1505-Horrabin05a

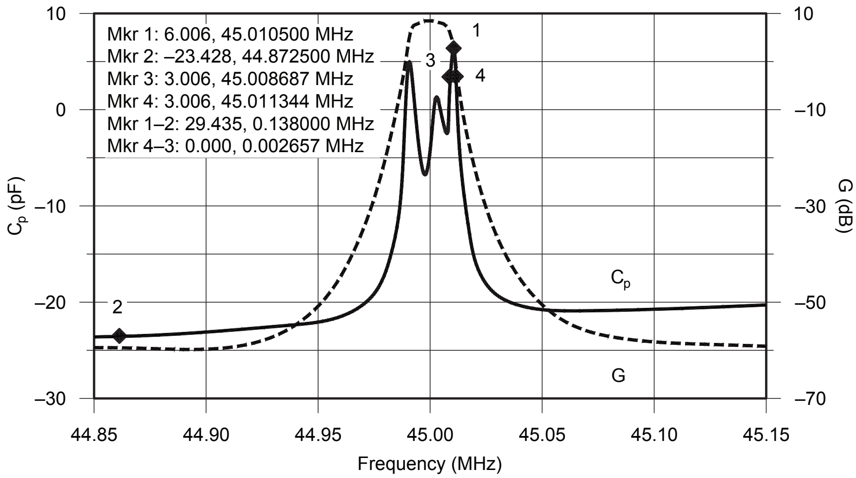
(A)


Mkr 1: 8.466, 45.001500 MHz
Mkr 2: –61.155, 44.872500 MHz
Mkr 3: 5.466, 44.990814 MHz
Mkr 4: 5.466, 45.009389 MHz
Mkr 1–2: 69.620, 0.129000 MHz
Mkr 4–3: 0.000, 0.018575 MHz
RL
G
G (dB)
Frequency (MHz)
QX1505-Horrabin05b

(B)

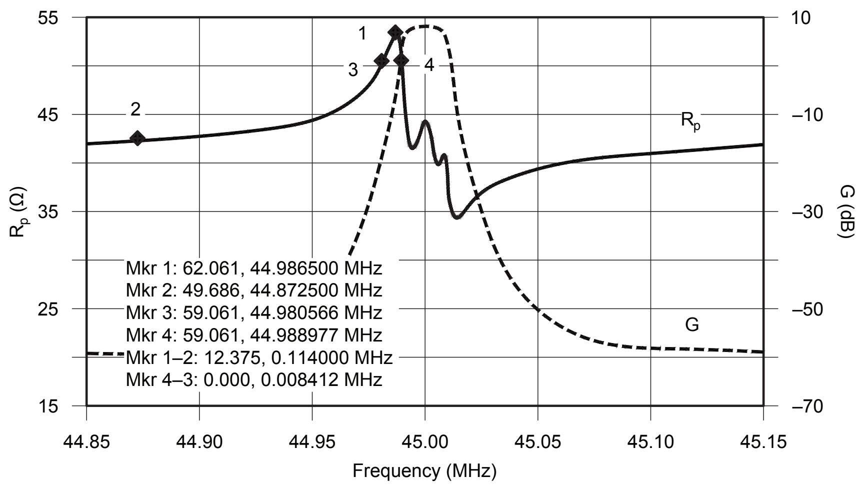

Zs (Deg)
Zs (Ω)
Mkr 1: 62.061, 44.986500 MHz
Mkr 2: 49.686, 44.872500 MHz
Mkr 3: 59.061, 44.980566 MHz
Mkr 4: 59.061, 44.988977 MHz
Mkr 1–2: 12.375, 0.114000 MHz
Mkr 4–3: 0.000, 0.008412 MHz
Zs (Ω)
Zs (Degrees)
Frequency (MHz)
QX1505-Horrabin05c

(C)



QX1505-Horrabin05d

(D)



QX1505-Horrabin05e

(E)

Figure 5 — These graphs are the performance measurements made by Dave Roberts using his N2PK vector network analyzer.

quadrature hybrid. For an amplifier output level of 0 dBm, each amplifier has an output of –3 dBm. Because it has a gain of 18 dB, the amplifier input level and the 6 pole crystal filter output level is –21 dBm. This gives an input level to the crystal filter of –17 dBm, and an input level to the complete amplifier of –14 dBm. This ties in with the measured performance of the unit as a gain block with a gain of 14 dB and a noise figure of 6 dB.

The main measurements of in band and out of band IP3 were made at an amplifier output level of 0 dBm. A few out of band measurements were made at a 10 dBm output level (shown in parentheses in the table) to give some idea of the linearity of the unit with signal amplitude. The projected IP3 of a receiver using this amplifier assumes a 5 dB mixer loss and 2 dB loss due to its input low pass filter. So effectively, the input intercept of the 45 MHz amplifier module has 7 dB added to its input IP3 to calculate the receiver performance. This presumes that the amplifier is used with the HF7070 front end. It is unlikely that the out of band IP3 of such a receiver will exceed 45 dBm, but Table 1 does show that the IP3 performance of the radio will not be limited by the IP3 of the roofing filters.

Figure 8 is a screen shot from the spectrum analyzer, with the test tones 2 kHz apart but offset by a few hundred hertz. The offset is necessary to identify the third order product, because at this spacing of the signal generators there are spurious peaks from the signal generators on integer boundaries. For the out of band measurements, the signal generator frequencies again had to be offset slightly because there was a low level spurious peak from the signal generator at exactly 45 MHz.

Observations

Using this amplifier to replace the 45 MHz IF amplifier in the HF7070 receiver makes possible a receiver IP3 performance of 50 dBm at 20 kHz tone spacing, for a receiver noise figure of 13.5 dB. In addition, the in-band dynamic range is also significantly improved and that was the real reason for constructing this IF strip using the PHA-11+ MMIC. In fact for in-band signals it is now the IP3 performance of the ADC that is the limiting factor. Improve the ADC and an in-band IP3 of over 30 dBm at 100 Hz spacing is possible for an up-conversion radio. The MMIC has gain at 3 GHz, and fortunately there has been no sign whatsoever of any instability with the circuit during testing. The circuit board layout and the Pi match capacitors close to the input of the chip have probably helped in this regard.

It is very unlikely that John Thorpe will incorporate this prototype amplifier into one of the HF7070 prototypes, to test it as part of a real radio receiver. With John, you never can tell, however!

The PHA-1+ / PHA-11+ MIMC is unsuitable for application in down conversion receivers for the amateur bands but could be used to give state of the art performance in an up-conversion radio with simple circuitry. If you are interested in a state of the art receiver for the amateur bands then PA3AKE's holy grail version of the CDG2000 transceiver is definitely the way to go. By publishing details of this 45 MHz MMIC IF amplifier, perhaps it might be incorporated into some shortwave radio transceivers. In principle the result could be a state of the art up-conversion receiver at a budget price. Mini-Circuits now supply the PHA-22+ MMIC. It looks like a 1.5 GHz version of the PHA-11+ so it should be of lower cost and a drop-in part for this application.

The noise figure of the MMIC chip used in the amplifier adds directly to the receiver noise figure. Mini-Circuits do make chips with 0.5 dB noise figures, but in most of these their performance below 100 MHz is unsuitable. Those that have a very low noise figure below 100 MHz have too much gain. In fact the PHA-1/PHA-11 appears to be the ultimate part made by Mini-Circuits for this sort of application at the present time.

This amplifier has been built into a tin box to get a good stop band and also so that a complete IF module could be mounted onto a circuit board motherboard. It is likely any potential manufacturer of a transceiver would want it to be part of the main circuit board. The 45 MHz monolithic crystal filters used in the HF7070 proto 2 receiver were obtained from the British company Total Frequency Control (TFC). The 6 pole filters used in this prototype 45 MHz amplifier were made up by splitting 4 pole pairs. Total Frequency Control's Japanese supplier does in fact make a 6 pole, 15 kHz bandwidth, 45 MHz monolithic crystal filter in one can. This has a poor stop band, however. They have been asked if they can produce a 6 pole filter with a 110 dB stop band at ±90 kHz. They could probably achieve this by constructing it in a larger can.

One problem with the HF7070 receiver was coupling between the two toriods used as part of a quadrature hybrid. Mini-Circuits makes a shielded quadrature hybrid centered on 45 MHz. So it may be possible to build this circuit on the main circuit board and get a 110 dB stop band at the second mixer image frequency.

I sent a copy of the circuit and the IP3 measurements to several American friends for their comments. Wes Hayward, W7ZOI, was amused that we have spent so much time and effort and our own money on this project because it is only of use to an "appliance" manufacturer and not for normal Amateur Radio projects. The *QEX* article on the HF7070 receiver showed

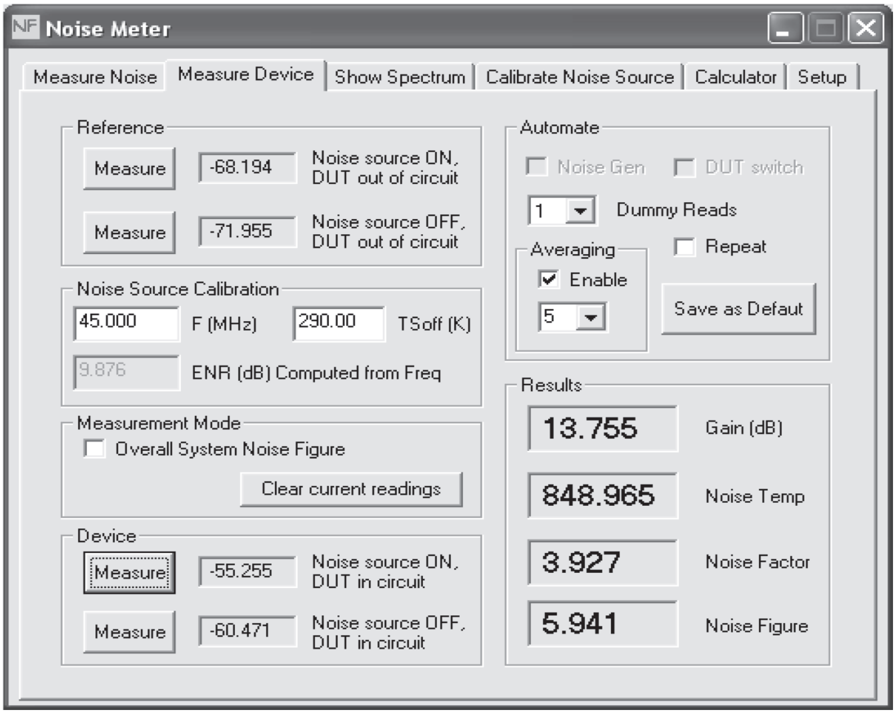


Figure 6 — This screen shot shows the results of the noise figure and gain measurement made by Dave Roberts.

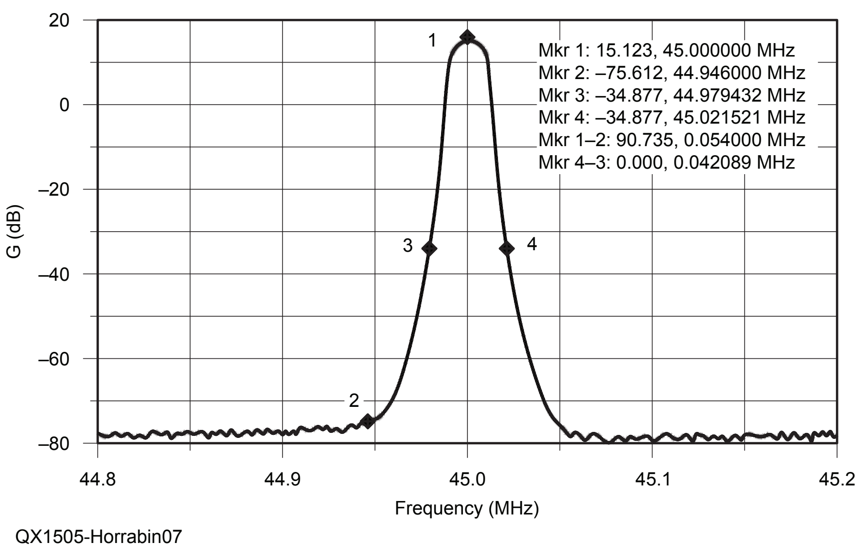


Figure 7 — This graph is the result of a second measurement of the circuit transmission characteristics made with Dave Roberts' vector network analyzer, after internal shields were installed between sections of the circuit.

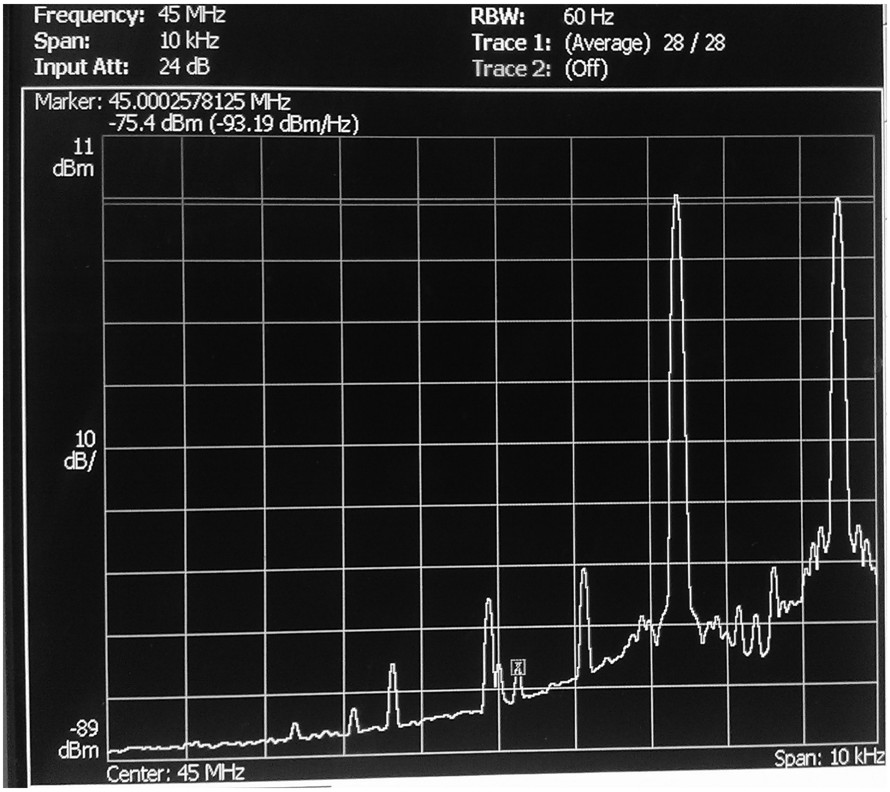


Figure 8 — This screen shot is the spectrum analyzer two-tone test measurements the author made at Daresbury Laboratory. The input tones were 2 kHz apart. The analyzer is set to a center frequency a few hundred hertz offset from the center of the tones.

that it should be possible for main stream “appliance” manufacturers to make a good up-conversion receiver that will outperform most commercial down conversion receivers. The application of the PHA-11+ in a 45 MHz IF amplifier can further improve the IP3 performance of an up-conversion radio like the HF7070, and also simplifies the circuit in that only one chip is required in the 45 MHZ IF amplifier.

Acknowledgements

This project needed the use of machine tools, and I would particularly like to thank my neighbor, Alan Heywood, for doing all the mechanical work.

Our friend Martein Bakker, PA3AKE, ordered and generously paid for the commercial circuit board with its thermal vias, and checked the circuit board files before they were sent to Fischer in Germany for manufacture.

Since Dave Roberts has an N2PK VNA and the capability to measure noise figure, it was only necessary to visit Daresbury Laboratory to measure IP3. As usual, my former colleagues were most helpful even though they were particularly busy at the time. I want to single out the help given by Andy Moss in the RF group, and Nigel Lightbown, who did the reflow soldering of the PHA-11+ chips onto the circuit board in the electronic workshop.

There was a problem in getting samples of the Mini-Circuits PHA-11 + MMIC from the US, because they wanted to sell only the minimum reel size, which came to about $300. John-Paul Newbold of Minicircuits Europe supplied us with some he bought on his own budget, however. He obviously realized the potential of this application of the chip in up-conversion radio receivers when others didn’t.

Mark Sumner of MWS Technical Services provided the 45 MHz crystal filters that were made by Hertz Technology in Japan for use in the amplifier. Although these filters are no longer commercially available, those supplied by the British firm TFC Ltd have similar IP3 performance, and they were fitted in the HF7070 proto 2 receiver on which the technical performance measurements were made. Those measurements are presented on Martein Bakker’s website.

Finally, although most consumer electronic products these days originate in the far east, it is still American companies that drive fundamental technological advances, of which the Mini-Circuits PHA-11+ is one such example. It remains to be seen how long it will be before it is used in commercial Amateur Radio equipment designs.

Appendix A: Variations on a Theme

In the present circuit, the output of each arm of the six poles of crystal filter went to one of the amplifiers in the PHA-11 and the outputs of the two amplifiers were combined by the second quadrature hybrid.

Two other circuits were considered that used a single device. In both these circuits the outputs of the two arms of the six poles of crystal filter were combined by the second quadrature hybrid before a single amplifying device. The devices considered for this were two Mini-Circuits MMICs: the PHA-1+ and the very low noise PGA-103+.

There were two main reasons for the present architecture. The first being that the quadrature hybrid input network seen by a MMIC is effectively a “floating” circuit. Because the MMICs have gain at 3 GHz we thought that the series inductance and parallel capacitance to ground of a Pi network at the input to the MMIC in the present architecture would give less chance of instability. Also the output IP3 would be increased by 3 dB and the output quadrature hybrid would present a good match to the second H-mode mixer.

If a single PHA-1+ MMIC is used in the alternative architecture at 45 MHz, the noise figure (NF) of the chip would be around

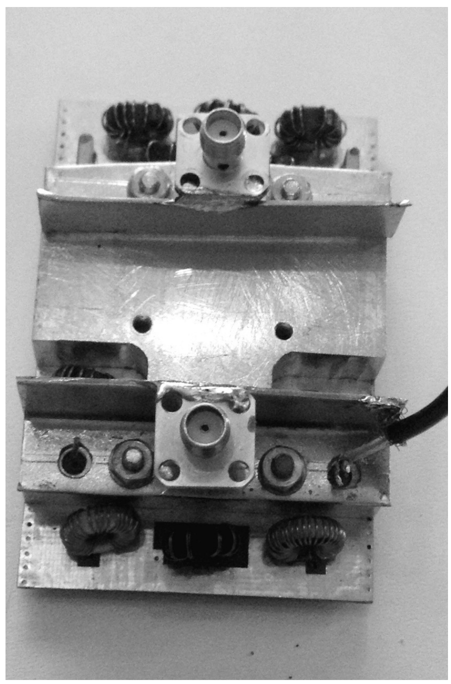


Photo B — This photo shows the component side of the completed 45 MHz IF amplifier circuit board, attached to the aluminum bar shield/heat sink. The SMA connector at the top of the photo is the RF input and the one at the bottom is the RF output. The length of small coaxial cable brings the 5 V supply to the circuit board.

2 dB, with a gain of 18 dB, an IP3 out of 43 dBm, and the output IP3 of the hybrid connected filters would be about 27 dbm for in-band signals. Putting these figures in John Thorpe's spreadsheet gives a receiver NF of 13.6 dB, an IP3 of 26.3 dBm, and a dynamic range in a 2.4 kHz bandwidth of 101.8 dB for close-in signals. The loss because of the six poles of crystal filter and two hybrids is around 4 dB.

The PGA-103+ at 45 MHz has a very low noise figure of 0.5 dB a gain of 26 dB and an output IP3 of 37 dBm. Putting these figures into the spreadsheet gives a receiver performance of NF of 11.6 dB, an IP3 of 20.3 dBm, and a 99 dB dynamic range in a 2.4 kHz bandwidth. This is close to the performance of the HF7070 receiver using the 4 × J310 amplifiers. The other difference would be that the out of band IP3 from 20 kHz outwards would be superior to the present HF7070 receiver.

In both of these circuits the gain of the HF7070 in the spreadsheet for the 44 kHz balanced amplifier was changed so that the total gain from antenna to the 25 bit audio ADC was the same, at 22 dB.

Commercial design can be all about compromise, so the use of the PGA-103+ could be the chosen option to avoid the use of a preamplifier with the receiver above 7 MHz. Where the present architecture will score (and also if a single PHA-1 is used) is that it will have a much better IP3 in the crystal filter transition region for test tones from 5 kHz to 20 kHz than if a PGA-103 + was used. This all presupposes that the MMICs will not become unstable when driven by the output from a quadrature hybrid.

Having demonstrated the use of the PHA-11+ MMIC in this type of 45 MHz IF amplifier, I will leave it to others to try the other options described, to see if these circuits remain stable when driven directly from a quadrature hybrid.

Colin Horrabin, G3SBI, was born in 1941. His father provided him with a World War II BC348 radio receiver for his 12th birthday, followed by a copy of the ARRL Handbook *for Christmas. After years building various projects using government surplus equipment, he obtained his Amateur Radio license in 1963. He has a degree in electrical engineering and a degree equivalent qualification in mechanical engineering. Following an apprenticeship with the British Aircraft Corporation in the early 1960s, he spent over 30 years working at Daresbury Laboratory as an electronic engineer. Colin is interested in small DX antennas for the LF bands, and intends to do some work on small multi turn spiral wound loops that are self resonant, containing ¼ wavelengths of wire, which are suitable for transmitting.*

Reference Material

See the Mini-Circuits website for data on the PHA-1+ / PHA-11+ / PHA-22+ and the PGA-103+ MMICs and other interesting parts: **www.minicircuits.com**.

Reed Fisher, W2CQH, "Twisted-Wire Quadrature Hybrid Directional Couplers," *QST*, Jan 1978, pp 21 – 23. Note that better results at VHF can be achieved by using bonded bifilar wire with the added practical advantage that each wire has a different colored enamel. Such wire is available from the Scientific wire Company (**www.wires.co.uk**).

The "Instruction Manual" for the L/C Meter IIB from Almost all Digital Electronics, USA: **www.aade.com**.

Data on Micrometals T37-10 powdered iron RF toroids is available on the Micrometals website: **www.micrometals.com/rfparts/rftoroid3.html** and various vendor websites.

G R Jessop, G6JP, *Radio Data Reference Book*, Fifth Edition, 1985 (RSGB Publication) page 58, "Pi and L-Pi Network Couplers — Improved Design Methods" (about lower impedance ratio matching circuits).

The N2PK VNA by Paul Kiciak, N2PK, (**http://n2pk.com/**) with modifications by Ivan Makarov, VE3IVM, (**www.makarov.ca/vna.htm**) and a USB interface and *Windows* application software by Dave Roberts, G8KBB (**www.g8kbb.co.uk/**).

Dave Roberts, G8KBB, "The measurement of Noise," *RadCom*, Jan 2007 pp 70 – 80. This is an article about Dave's noise figure measuring system.