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Ultralinear 2N5109 And 2N3053 Amplifiers

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For about a year I have been experimenting with extremely high intercept amplifiers using 2N5109 and 2N3053 bipolar junction transistors (BJT's). These kinds of amplifiers, known as common base transformer feedback (CBTF) amplifiers, and also known as common base noiseless feedback (CBNF) amplifiers, if properly designed and used, offer MW DXers (and SW DXers, though their needs are not as extreme as MW DXers) amplifiers with extremely low levels of 2nd and 3rd order intermodulation distortion (IMD2 and IMD3), which, in turn, offer much higher levels of strong signal handling performance than have been available previously. CBTF amps can provide greatly improved performance for balanced two foot air core loop amps, for low-gain tuned preselector amps, for broadband phasing system amps, and for other similar applications where extremely high 2nd and 3rd order input intercepts (ICP2in and ICP3in) are needed. Appropriately configured, a single BJT CBTF amp can have ICP3in greater than +35 dBm throughout the MW band and ICP2in greater than +46 dBm throughout the MW band. With a pair of BJT CBTF amps configured push-pull, ICP2in greater than +95 dBm can be achieved throughout the MW band. The purpose of this note is to summarize my experiences with CBTF amps using 2N5109 and 2N3053 BJT's, and to provide enough information for other DXers to construct and use these kinds of CBNF amps.

CBNF/CBTF amps were first described by Dr. David E. Norton in his pioneering May 1975 Microwave Journal article, "High dynamic range transistor amplifiers using lossless feedback." The amplifers were patented (U.S. Patent Nos. 3,426,298; 1969, 3,624,536; 1971, and 3,891,934; 1975), which, perhaps, explains why CBTF amps have not been widely used in the past. According to reliable sources, these patents have expired. However, if you decide to produce and sell such amps, you should obtain legal counsel to verify this information. In that pioneering article, only transformer turns ratios and corresponding amp gains were given; no information about DC power and biassing was given; see Fig. 1 at left. A theoretical circuit analysis based on simplifying assumptions was given as follows. Assuming that a common base BJT amp has zero input impedance, and infinite output impedance (neither of which is true), and assuming unity current gain (which is approximately true provided the operating frequency of the amp is well below the cutoff frequency of the BJT), a two way impedance match to Z_0 will be obtained if the transformer turns ratios $n_1:n_2:n_3$ satisfy the turns ratio condition 1:n:m where $n = m^2 - m - 1$. Permissible ratios include 1:1:2, 1:5:3, 1:11:4, 1:19:5, and so on. Also with the above simplifying assumptions, power gain is m^2. Thus, a 1:1:2 amp has gain 4, or 10 log(4) = 6.o2 dB, a 1:5:3 amp has gain 9, or 9.54 dB, a 1:11:4 amp has gain 16, or 12.04 dB, a 1:19:5 amp has gain 25, or 13.98 dB, and so on. The number of turns of wire on the transformer may be varied to adjust frequency range of the amp as long as the appropriate ratios are maintained. For example, a 1:5:3 amp may have 1:5:3, or 2:10:6, or 3:15:9 turns for $n_1:n_2:n_3$ and so on.

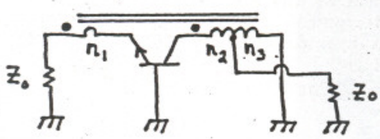

Fig. 1

The phasing dots of the transformer in Fig. 1 should be observed. A BJT CBTF amp uses negative feedback, so that reversal of the phasing of the feedback link n_1 would provide positive feedback, which would likely cause the amp to oscillate, and in any case would change amp gain, and degrade IMD performance and two way impedance match to Z_0.

Although it was not explained in Norton's pioneering article, the meaning of the expression "a two way impedance match to Z_0" is, apparently, that if one of these BJT CBTF amps works into a load of Z_0 ohms real, then the input impedance of the amp is Z_0 ohms. In other words, the input impedance of a BJT CBTF amp is dependent on the load impedance; namely, the input impedance is equal to the load impedance. But there is more to it than that. The transformer of the BJT CBTF amp is a broadband transformer, with a frequency range which depends on transformer parameters. So the frequency range for which a BJT CBTF amp provides a two way match to Z_0 is, presumably, no greater than the frequency range of the transformer. Also, the frequency range of a particular transformer depends on the source and load impedances of the transformer. This limits the range of values of Z_0 for which a particular transformer will provide a two way impedance match to Z_0 over a given frequency range. Based on experiments and measurements with a number of transformers, I have found that if the usual principles of broadband transformer design are adhered to, then a BJT CBTF amp using 2N5109 or 2N3053 BJT's has about the same frequency range as the transformer alone for a given Z_0. For many applications, Z_0 = 50 ohms, so the usual transformer design for 50 ohms should be used.

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The two way impedance match to Z_0 is an ideal characteristic of BJT CBTF amps based on a mathematical derivation which uses simplifying assumptions that are not true for actual common base amps, as pointed out above. Based on measurements with several BJT CBTF amps, I have found that if such an amp works into a load of Z_0 ohms real, then the input impedance tends to be about 60% to 80% of Z_0. I have not attempted to determine whether a perfect match to input impedance (using a broadband matching transformer) would increase the ICP2in and ICP3in of these BJT CBTF amps because the intercepts are already so high that there seems to be no need to raise them slightly higher by this means. Also, there are other easier means to raise the intercepts higher. For example, a 1:11:4 CBTF amp with appropriate transformer and biassing adjusted for 20 mA collector current and with appropriate bypassing and coupling capacitors has flat power gain of about 12 dB from about 100 KHz to beyond 30 MHz, while the ICP3in is about +38 dBm from 10 MHz to 30 MHz, but falls off slowly below 10 MHz to about +34 dBm at about 1.6 MHz, and to about +27 dBm at about 455 KHz. This decrease of ICP3in as frequency decreases seems to be normal and due to the diode junctions of BJT's. For higher ICP3in within and below the MW band, one may use a 2:11:4 transformer, which has a flat 6 dB power gain, and ICP3in greater than +35 dBm for all frequencies greater than 455 KHz. The two way impedance match of a 2:11:4 transformer is not perfect either, and gives an input impedance of about 160 % of Z_0. For a 2:11:4 CBTF amp working into a 50 ohms real load, this would be an input impedance of about 80 ohms, which is still a reasonably good match to a 50 ohms source impedance.

The example of a 2:11:4 CBTF amp above illustrates three of the general principles of negative feedback, namely that (1) as negative feedback is increased, power gain is decreased, (2) as negative feedback is increased, linearity improves (ICP3in increases), and (3) as negative feedback is increased, input impedance of the feedback amp is increased. An excellent discussion of negative feedback amplifiers is contained in Chapter 17 of the book Electronic Devices And Circuits, by J. Millman and C. Halkias, McGraw-Hill Book Co., 1967. There a fourth general characteristic of negative feedback amplifiers is discussed, namely the tendency of amp noise to decrease as negative feedback is increased, but I have not observed this characteristic in any of my experiments and measurements, perhaps because noise from other sources obscured any noise reduction which resulted from the higher feedback 2:11:4 CBTF amp.

My experiences with 2:11:4 CBTF amps, as related above, suggest that a fertile area for future investigation may be to study the performance characteristics of CBTF amps with transformer turns ratios other than the ideal ratios (1:1:2, 1:5:3, 1:11:4, and so on) originally proposed by Norton (and repeated by other writers). For example, it appears that the turns ratios for a near-perfect two way impedance match to Z_0 have yet to be determined for 2N5109 and 2N3053 BJT's, and since such amps have yet to be studied, their power gains and their input intercept characteristics are as yet unknown. And it appears that the only way to develop such amps, if they can be developed, is by trial and error, i.e., by winding transformers with different turns ratios and measuring the closeness of two way impedance match to Z_0, measuring amp gain, measuring ICP2in and ICP3in for various collector currents, and so on. One could also attempt to develop a more accurate mathematical model of CBTF amps beginning with the usual two-port hybrid models, but the complexity of such a project appears to be considerable.

Relatively little information appears to have been published regarding biassing CBTF amps using common BJT's, such as 2N5109 and 2N3053. The November 1984 Ham Radio column, "VHF/UHF World," by Joe Reisert, W1JR, contains the only biassing information I have found for a 2N5109. The same biassing was also suggested for an NEC NE4163B transistor. Another biassing arrangement, one for Motorola MRF586 BJT's, requiring +6 VDC and -6 VDC power sources, was discussed by J. Makhinson in his Feb. 1993 QST article, "A high-dynamic-range MF/HF receiver front end." However, the dual polarity power requirement makes Makhinson's approach difficult to implement, and based on experiments I have done, there is no improvement in linearity due to the dual polarity power arrangement. In part 2 of his Dec. 1981 Ham Radio article, "Communications receivers for the year 2000," Dr. Ulrich L. Rohde briefly summarized what Dr. David Norton had already published in 1976, and gave an example (in his Fig. 7) of an elaborate two-stage amplifier using the noiseless feedback concept. The two-stage amp used Siemens BFT66 BJT's, which are not widely available in the U.S.A. Due to the complexity of that two-stage amp, and because of the difficulty of obtaining BFT66 BJT's, it does not seem appropriate for hobbyist or consumer grade applications at MW's and SW's. Another example of CBTF amps was given in Rohde's Nov. 1992 QST article, "Recent advances in shortwave receiver design," namely, the use of an AGC controlled BFT66 CBTF IF amp (Fig. 11 of his article) in a Rohde & Schwarz EK0890 communications receiver.

Two schematics, one for the basic CBTF amp, and the other for a push-pull amp using two matched CBTF amps, are given below in Fig. 2. For MW band use, C1, C2, C3, C4, and C5 should be 0.1 or 0.2 uF, RFC1 should be 1 mH, RFC2 may be 100 uH or greater, up to 1 mH, FB should be an Amidon ferrite bead, type FB-101-64, T1 should be a Amidon FT-50-75 ferrite toroid core with n_1 = 1 turn, n_2 = 11 turns, and n_3 = 4 turns #24 enameled copper wire, and the 75 material core should be wrapped with thick Teflon tape before winding the wire turns, where the wire turns are spaced evenly around the entire circumference of the toroid core, R2 = 1000 ohms, R3 = 4700 ohms, and R3 = 10 ohms for +V DC = +9 volts DC, R1 should be a 100 ohm adjustable pot (I like Spectrol 25 turn

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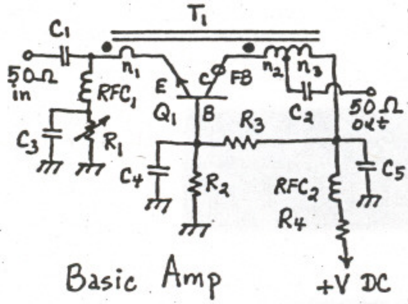
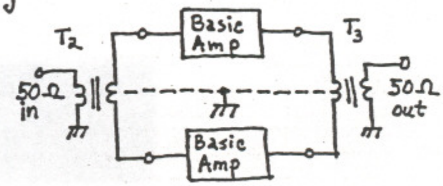
1/2 watt cermet top adjust pots in series with a 10 ohm 1/4 watt fixed resistor, the latter to prevent frying Q1 if the pot is accidentally adjusted to zero ohms), and Q1 may be either a 2N5109 or 2N3053. R1 is adjusted for whatever collector current is desired (up to about 16 mA if Q1 is not heat sinked, and up to about 30 mA if Q1 is heat sinked with a Mouser 567-7-120-BA heat sink rated at 35 degrees C/W ther. res.). The current drain (setting of R1) determines the amp ICP3in and ICP2in. More information about the relationship between current drain and ICP3in and the relationship between current drain and ICP2in will be given below.

Fig. 2



Basic Amp

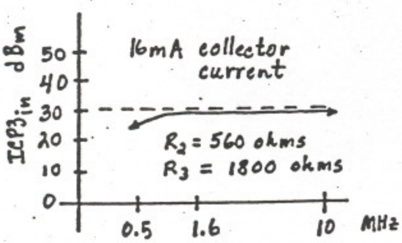


Push-Pull Amp

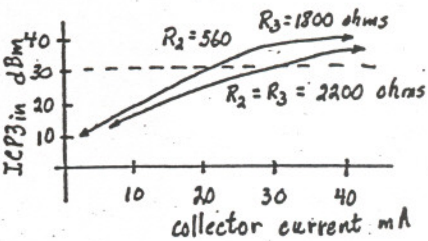
A push-pull (sometimes called balanced) CBTF amp requires a pair of basic amps configured as shown above in Fig. 2. For a push-pull amp with a frequency range of about 100 KHz to beyond 30 MHz, T2 and T3 should be Amidon FT-50-75 ferrite toroid cores, wrapped with thick Teflon tape, and wound with 8 bifilar turns of #24 enameled copper wire. The basic amps should be shielded from each other as shown in Fig. 2; otherwise, interaction between the individual amps may cause instability or degrade the extremely high ICP2in which this kind of push-pull CBTF amp is capable of achieving. It has been written in some publications that the individual amps of a push-pull pair do not need to be matched closely. That may or may not be true. I have not expended much effort to confirm or deny that statement. However, for all of my experiments and measurements I matched the individual basic amps as close as possible with h_{FE} of the BJT's matched to within 1 digit using a DVM with an h_{FE} range, all resistors 2% tolerance or less, the transformers T1 wound as identical as possible and with identical as possible lead lengths, T2 and T3 wound as identical as possible and with as identical as possible lead lengths, ferrite magnetic shielded chokes for RFC1 (Mouser 434-02-102J) to minimize mutual inductance coupling between the individual basic amps (chokes wound on FT-50-43 ferrite toroid cores might have been better for this purpose, but I could not detect any difference between the commercial Mouser chokes and hand-wound toroids in prototype amps which I tested extensively), and PC board construction with the individual basic amps laid out as identical as possible. Perhaps as a result of these precautions and attention to detail, I have been able to construct push-pull CBTF amps with ICP2in of about +100 dBm, which is substantially higher than has been reported for any previous amp, and especially for an amp with 12 dB power gain.

Because so little information was available regarding biassing, the relationship between ICP2in and collector current, the relationship between ICP3in and collector current, the relationship between ICP2in and frequency, the relationship between ICP3in and frequency, and so on, I made extensive studies of these issues and relationships. The results of those measurements are given below in Fig. 3.

Fig. 3



(a)



(b)

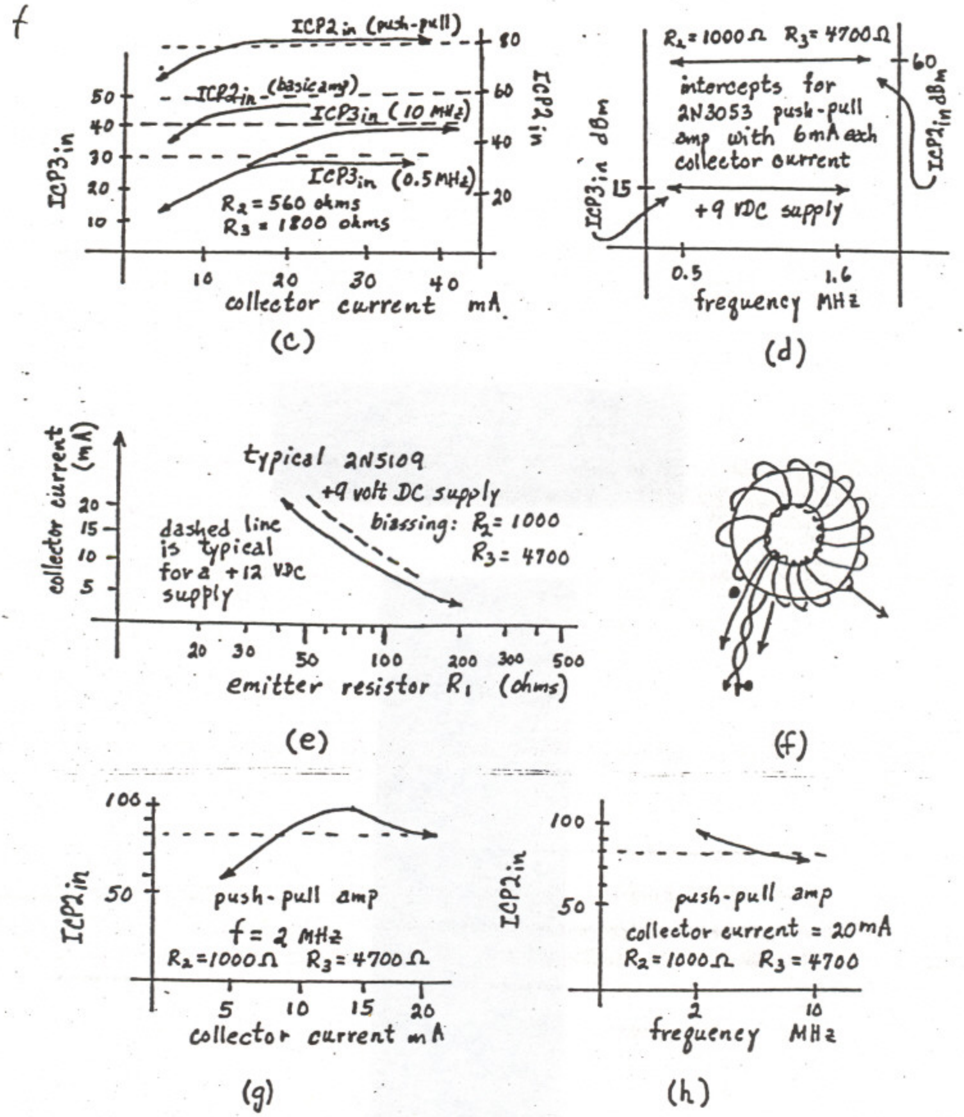


Fig. 3(a) shows the tendency for ICP3in to decrease as frequency decreases within and below the MW band. The biassing used there, R2 = 560 ohms and R3 = 1800 ohms, was the first biassing I tried. With other biassing, the relationship is different, but similar. Fig. 3(b) shows a feature of biassing: the ratio of R2 to R2 should be kept as low as practical to obtain maximal ICP3in with minimal collector current. R2 = 1000 ohms and R3 = 4700 ohms, which was recommended above for the basic amp of Fig. 2, provides a ratio of about 1/5, about the smallest practical ratio. For smaller ratios, adjustment of collector current via R1 becomes progressively more difficult. Also, smaller R2/R3 ratios would likely cause thermal instability of ICP2in for the push-pull amp, and make maximum ICP2in via adjustment of R1 difficult, if not impossible, to obtain. Fig. 3(c) compares the relationships between ICP (2 and 3, push-pull and basic amps) and collector current. It should be observed that for a given SW frequency (10 MHz in this case), a "knee" occurs in the ICP curves, and that for greater collector currents beyond this "knee," little or no increase in ICP is obtained. But this is not the case for ICP2in at lower frequencies; see Fig. 3(g) and Fig. 3(h). Fig. 3(d) shows that much higher ICP2in can be obtained in the MW band with a push-pull CBTF amp drawing very low collector current (6 mA in this case) than has been reported for any other kind of amp. Such an amp might be ideal as a two foot air core balanced MW loop amp. The point I want to make here is that the +100 dBm ICP2in which can be achieved with a push-pull CBTF amp is "overkill" for a two foot air core loop amp (unless you want to DX in the shadow of a 50 KW transmitting tower), and that lower collector currents (exactly how much lower, I don't know) would be entirely adequate for such an application. Fig. 3(e) shows how collector current varies with R1 value for a typical 2N5109 BJT when R2 = 1000 ohms and R3 = 4700 ohms. Typically somewhat lower R1 values are required for a 2N3053. The purpose of this graph is to give you a starting point for adjusting collector current. Fig. 3(f) is a sketch of T1, a negative feedback transformer wound on a toroid. As mentioned previously, the spacing of the turns is uniform around the entire circumference of the toroid. To get a snug fit, and to preclude the one turn feedback link from making physical contact with the semiconductor material of the 75 material toroid, it is helpful to use a short length of insulation over the wire of the one turn link.

All of the graphs of Fig. 3 were developed for CBTF amps using a 1:11:4 feedback transformer, i.e., for 12 dB power gain CBTF amps. Similar results may be obtained for CBTF amps with other turns ratios, but I have not made

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exhaustive studies of those cases, merely some spot measurements to determine if the results for those other cases were similar (they were).

Don't let the myriad of variations of biassings, collector currents, and operating frequencies dissuade you from constructing a CBTF amp or two. Even if you don't get the amp quite optimal for your intended application, the chances are that your end result will be considerably better than any other amp you have ever built. Except for the chokes (which can be ordered from Mouser) and the toroid and ferrite bead (which can be ordered from Amidon), the basic amp of Fig. 2 can be built entirely with parts purchased at Radio Shack if you are willing to live with a less than optimal amp. Use a 100 ohm fixed resistor for R1, and use R2 = 560 ohms and R3 = 1800 ohms. All of the required resistors are available in the resistor package Cat. No. 271-312A. Radio Shack also carries the 2N3053, which, with an f_T of 100 MHz, is suitable for use up to at least 30 MHz. (The 2N5109 is really only necessary if you need to scale the amp up into the tens to hundreds of MHz range, and in that case you will need to replace all the capacitors with 1000 pF capacitors, and use entirely different transformers.) With the above biassing, collector current should be in the 14 to 16 mA range, and heat sinking should not be required. As a matter of fact, I used the above biassing for all of my early experiments with CBTF amps, with impressive results which continually astonished me. Although I used 2N5109's instead of 2N3053's, subsequent experiments and measurements have shown that 2N3053's provide virtually identical performance. I discovered the 2N3053 quite by accident one afternoon at Radio Shack while digging through the racks looking for something else. When I spotted the 2N3053, it looked just like a 2N5109, so naturally I plucked one off the rack and read the specs on the back of the package. Except for a lower f_T, the specs were very similar to a 2N5109. For all I know, the 2N3053 is a 2N5109 which failed the 1.2 GHz f_T test for a 2N5109. Anyway, I immediately bought a few and hurried home to try out the 2N3053 in place of 2N5109's in amps laying around on my work table. They were fine; same gain, same low noise, and only slightly less collector current (and, thus, slightly lower intercepts) for a given R1. To get virtually identical performance to a 2N5109, one only needed to adjust the value of R1 slightly. This experience led to a curious excursion into old transistor reference books. I was sure that I had searched old handbooks for possible substitutes for the 2N5109 and had found none. And indeed I had. In 1967 and 1969 RCA transistor handbooks the 2N3053 was listed as having an f_T of 20 MHz, so I had concluded that it would not be suitable above, say, 10 MHz. Current production 2N3053's appear to be entirely different BJT's from the 1967/69 versions. Similarly, further research revealed that current production 2N5109's have entirely different parameters from 1967/69 2N5109's. This could have a bearing on why current production 2N5109's (and 2N3053's) do not provide a near-perfect two way impedance match to Z_0 as discussed above. In any case, the 2N3053 appears to be entirely adequate for use up to at least 30 MHz. With 0.1 uF capacitors, the basic amp of Fig. 2 has flat gain down to about 150 KHz, with gain falling off slowly below 150 KHz. For flat gain to 100 KHz, 0.2 uF capacitors are required. I have not attempted to extend the frequency response below 100 KHz, but I see no reason why it could not be done. I would suggest that each capacitor be a 0.2 uF monolithic ceramic capacitor in parallel with a 2 uF tantalum. All of the turns of the feedback transformer T1 should be doubled, i.e., $n_1:n_2:n_3$ = 2:22:8. Probably smaller guage wire, namely #26 or #28, will have to be used. If gain falls off above 10 KHz, try 3:33:12 turns. If 12 dB gain is more gain than you need for your intended application, try the 9.5 dB gain version with 2:10:6 turns of #24 enameled copper wire, which should give flat gain from below 100 KHz to well above 30 MHz. A 3:15:9 turn version should be good down to 10 KHz (with 2 uF // 0.2 uF caps), but high frequency gain will begin to fall off above 15 MHz or so. For various reasons I didn't like the 6 dB gain 1:1:2 version. If a 6 dB gain CBTF amp is your cup of tea, try the 2:11:4 version which I discovered. It has much higher ICP3in than the "standard" 1:1:2 version anyway.

A push-pull CBTF amp requires somewhat more careful implementation than the basic amp. Nevertheless, the reward is well worth the effort: complete elimination of 2nd order intermodulation distortion products if implemented and used correctly. With the aid of a DVM, you should be able to obtain the required 2% or closer tolerance resistors from a Radio Shack 271-312A package as I did for my initial experiments. And if memory serves me correctly, I obtained one pair of 2N3053's matched to within one h_{FE} digit from a batch of five 2N3053's off a Radio Shack rack. Since you probably won't have an intermodulation distortion measurement system capable of measuring 2nd order intercepts of +80 dBm, much less +100 dBm, you probably won't be able to adjust a push-pull CBTF amp for maximum ICP2in. However, you will still have an amp with intercepts of about +80 dBm merely by matching the resistors and 2N5109's or 2N3053's as described above. If you will order some 1% tolerance 10 ohm 1/4 watt resistors from Mouser (or your favorite supplier), you can probably do even better by trying different resistors for one and/or the other R1 resistors of the basic amp pair until you have made the collector currents of the two basic amps as nearly equal as possible, where collector currents are measured by measuring the voltages across the two 1% tolerance 10 ohm resistors R4 in each of the basic amps. Or you can simplify this adjustment by using the 25 turn 100 ohm cermet pots recommended previously for the basic amp of Fig. 2. In that case, one pot is set for approximately the current drain desired (again, current drain is measured by measuring the voltage across the 10 ohm 1% tolerance resistor R4 for that amp), and then adjusting the other pot until both collector currents are equal (as indicated by equal voltages

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across both resistors R4). If you do have an intermodulation distortion measurement system capable of measuring 2nd order intercepts in excess of +100 dBm (which is unlikely), then you merely adjust the collector current of one of the pairs to whatever value is desired, and while observing a 2nd order product produced by the CBTF amp, adjust the second pot to minimize the 2nd order product. Don't even attempt to adjust the push-pull CBTF amp in this manner unless you are certain you know what you are doing. To the best of my knowledge, there is no other intermodulation distortion measurement system than my own which is capable of accurately and reliably measuring 2nd order intercepts in excess of +100 dBm.

The R1 = 100 ohms, R2 = 560 ohms, R3 = 1800 ohms amps discussed above should have collector currents of about 16 mA (32 mA total for the push-pull), and if they do, then they will not need to be heat sinked. If you decide to operate them at higher collector currents (say, to obtain higher ICP3in), then they should be heat sinked. Many heat sinks are not easy to use, and some are impossible to use. The Mouser 567-7-120-BA heat sink is one of the easier heat sinks to use, but still difficult. The main problem with many heat sinks for TO-39 cases is that the metal material of the heat sink is not flexible enough to make it easy to mount the heat sink on the TO-39 case. I use small screwdrivers as miniature wedges to slowly open up the Mouser heat sinks until at some point a TO-39 case can be slid into the heat sink with the screwdriver still wedged into the top of the heat sink slot, so that when the wedge (screwdriver) is removed, the heat sink fits <u>tightly</u> (and I do mean <u>tightly</u>). I do not try to wedge the heat sink open in one try, but begin with the smallest possible screwdriver, and move up through progressively larger (but still small) screwdrivers until the condition above is achieved.

You should not pry on the heat sink with a twisting action of the screwdriver. That will cause deep scratches and metal burs on the heat sink, which will make it more difficult to use, and perhaps degrade its heat dissipation characteristics. The Mouser heat sink should be adequate for up to about 30 mA continuously. However, there really is no good reason to run a CBTF amp much above 25 mA because, as shown in Fig. 3, with appropriate biassing, the increase in ICP3in above 25 mA is negligible. And if maximum ICP2in is desired, optimal collector current is in the 13 to 15 mA range, where no heat sink is required.

Fig. 4

I already had several kinds of heat sinks on hand (but not the Mouser 567-7-120-BA) when I started operating CBTF amps at higher collector currents (which require heat sinks). But I did not like any of the heat sinks I had at the time, mainly because they were difficult, if not impossible, to adjust for proper tightness of fit. So initially I made my own heat sinks from 0.021 inch thick copper plate, cut into 11/16 inch wide by 2.5 inch long strips, and bent into the shape shown in Fig. 4 using the shank of a 5/16 inch drill bit. The 0.021 copper plate was obtained from my local sheet metal shop. It is the standard copper plate used to make copper gutters locally. I was given scrap pieces free of charge. They would probably have cut it to the 11/16 by 2.5 size, but I did not know what size I wanted when I got the scrap copper plate. I used a nibbling tool to fabricate several sizes for testing. The 11/16 by 2.5 size turned out to be sufficient for heat sinking up to about 25 mA continuous collector current, and up to about 40 mA collector current for brief periods. Wider strips may be used for continuous collector currents above 25 mA. Tightness of fit can be adjusted easily with finger pressure: bend the interior circle together until the circle is almost closed, and it should be difficult (but not impossible) to insert a TO-39 case by hand. Removal of a TO-39 case from this heat sink is best done with the aid of a short piece of 3/16 inch or 1/4 inch hardwood dowel. The collectors of 2N5109's and 2N3053's are connected circtly to the cases, so the cases, and, consequently, the heat sinks, are at +V DC volts. That is one reason why tight heat sink fit is required. The heat sink should not move around, and possibly short the DC supply. The other reason for tight heat sink fit is to provide good thermal contact.

The collectors of these kinds of CBTF amps should be at about +9 volts DC. However, with higher collector currents, a single basic amp will be a "battery eater." If you already have a +12 volts DC supply, use dropping resistors in series with the 10 ohm resistors R4 to adjust the collector voltage to about +9 volts DC. It is not necessary to operate the collectors at exactly +9 volts DC. Anything between about +9.0 and +9.5 volts DC is fine. Here is an example of how to estimate the required dropping resistor. Suppose you have a regulate 12 volt DC supply which puts out +12.4 volts with no load. And suppose your target is a single CBTF amp drawing 21 mA collector current. And suppose you decide to run it a +9.1 volts DC collector voltage. You merely plug into Ohms Law (V = IR), 3.3 = 0.021 R, and solve for R, R = 3.3/0.021 = 157 ohms. The nearest common standard resistance value is 150 ohms. Reversing the calculation, V=0.021 x 150 = 3.15 volts. So when a 150 ohm resistor is used, if the CBTF amp is adjusted for 21 mA, the voltage drop across the 150 ohm resistor is about 3.15 volts. There is an additional voltage drop of V = 0.021 x 10 = 0.21 volts DC across the 10 ohm resistor, so the collector voltage for the +12.4 volts DC supply should be about 12.4 -(3.15 + 0.21) = + 9.04 volts DC. A +12 volts DC supply is actually a better choice than a +9 volts DC supply because the dropping resistor (150 ohms in the discussion above) improves the thermal stability of the CBTF amp (if the amp attempts to draw more current, say, because the amp temperature rises, then the dropping resistor drops more voltage, and the collector voltage would decrease, causing the BJT to draw less current, cool down, and return to its previous operating point). Also, such dropping resistors provide additional isolation of the DC line, and high DC line isolation is important for proper operation of both the basic amp and the push-pull amp.

The discussions above are for CBTF amps with fixed resistors for R1. If you make R1 adjustable, with a 10 ohm fixed resistor in series with a 25 turn 100 ohm cermet pot, then you may omit the dropping resistor (150 ohms in the discussion above) and adjust the collector current(s) for your target value. The DC line isolation will not be quite as high, but it should not matter. I have operated CBTF amps both ways, and I can't find any measurable difference between the two approaches. Russell Scotka has been using a push-pull 12 dB gain (1:11:4) CBTF amp which I sent him several weeks ago as part of a broadband phased antenna system he has been developing, and I set the amp up for operation with a +12.0 volts DC power supply without dropping resistors. Russ' phasing system is the one described on page 75 of Victor Misek's <u>The Beverage Antenna Handbook</u>, Second Edition. That system uses a VN66AF power FET amp drawing about 90 mA current with a 12 volt DC power supply. With the power FET amp, Russ had several IMD products (all, apparently, 2nd order products). With the push-pull (dual 2N5109) CBTF amp I sent Russ, all IMD products completely disappeared. Russ lives in a high RF urban MW environment in Margate, FL, near Miami, so I doubt there could be a more convincing testament to the effectiveness of a push-pull CBTF amp than the pounding Russ exposed it to. If memory serves me correctly, I set Russ' amp for about 25 mA collector current for each of the basic amps of the push-pull pair, i.e., for a total current drain of about 50 mA. This illustrates an important feature of CBTF amps: you get higher intercepts with rather modest current drains compared to other approaches. Actually, this is not a fair comparison because the power FET amp in Misek's original circuit is not push-pull, and the residual IMD experienced with the power FET amp is, apparently, 2nd order. However, a push-pull version of Misek's amp would require two power FET amps, with a total current drain of about 180 mA. So a push-pull CBTF amp is clearly a better choice for this application based on current drain considerations alone. Also, it is unknown whether a push-pull VN66AF power FET amp would have similar intercepts to a push-pull CBTF amp with the p-p-p FET amp drawing 180 mA.

A free-hand sketch of the bottom view of a PC board layout for a push-pull CBTF amp is shown below in Fig. 5. The sketch was drawn enlarged by 1.5625 so that when Fig. 5 is reduced by 0.64 it will be more-or-less exact size. The sketch in Fig. 5 was also drawn enlarged because it would have been impossible for me to produce an exact size drawing. I produced the PC board with Radio Shack dry-transfers and resist pen. The current dry-transfers available at Radio Shack are virtually useless; they don't stick well, they split, and they tend to wash off while the board is being etched. But if you are determined, like me, you can use them. I should explain certain peculiar features of the PC board layout, namely the unused pads. Some of the unused pads are for paralleling bypass and coupling/blocking capacitors. It is sometimes difficult to obtain monolithic ceramic capacitors with values larger than 0.1 uF, so I allowed for paralleling 0.1 uF capacitors to obtain the required 0.2 uF capacitors for flat gain to 100 KHz. I was also unsure if I should parallel 0.2 and 0.0047 uF capacitors for better bypassing and coupling from 100 KHz to beyond 30 MHz (i.e., to maximize the broadband frequency range). I also wanted the option of having the collector currents adjustable with Spectrol, 1/2 watt, cermet, vertical, top adjust, 25 turn pots, or fixed (without the Spectrol pots, with fixed 1/4 watt resistors). And finally, I wanted the option of making the input or output push-pull (for example, to interface the push-pull amp directly with a two foot balanced air core loop, or to interface the amp directly with other balanced devices, such as noise reducing antennas, or receivers like the R-390A and HQ-180A with balanced inputs). So you will notice that either the input or output (or both) can be "floated" by removing the ground jumper(s), and that either side of the input and output transformers may be grounded. There are also several dark dots which denote holes drilled in the ground plane for ground pins or chassis tie points, and two for resistor ground points if the 25 turn pots are not used (which enable one to obtain non-standard resistance values by paralleling standard values). The cut-out along the center of the PC board is for a 1.75 inch long by 1.75 inch high rectangle of double sided 1/16 thich PC board which is required as a ground plane barrier between the two basic amps of the push-pull pair. The slot may be cut out with a thin emory grinder attachment of a Dremel tool, or with a miniature hack saw (in the latter case the slot will have to be started from one end, and the ground path at that end should be re-established with a heavy duty jumper).

If you don't like to or don't want to etch a PC board, you may use the Hayward & Hayward "ugly weekender" method to build the push-pull amp. Generally, the "ugly weekender" method involves using high megohm resistors as insulated standoffs (I use 4.7 meg ohm or higher). You can tack-solder the resistors directly to the copper foil of a piece of PC board, as they did, in which case the copper foil will face up towards the components. Or you can drill holes in the unetched PC board, stick resistor leads through the holes, bend the leads so that the bases of the resistors are flush against the insulated

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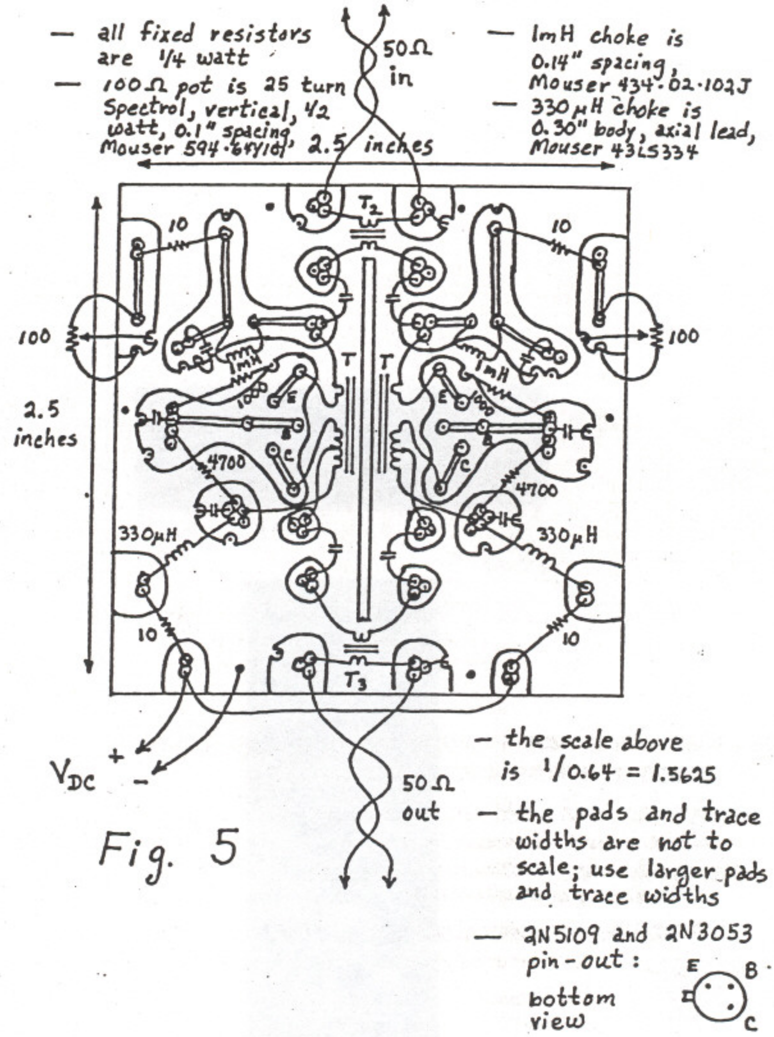

Fig. 5

PC board material, and solder the resistor leads, as I do. The unetched PC board provides an excellent ground plane for the circuit, and circuits constructed by this method work well up into the GHz range when RF is routed with miniature hard line coax. You will need a somewhat larger piece of PC board, say 3 inches by 3 inches, and the ground plane barrier between the two basic amps of the push-pull pair will need to be a bit higher, say 3 inches. As a matter of fact, the first push-pull CBTF amp I built with soldered connections used the "ugly weekender" method of construction, and that amp is currently performing flawlessly in Russell Skotka's broadband phased antenna system. I did not use the Spectrol pots in that version, but selected fixed resistor values by hand (using a DVM) to match the colelctor currents in the two basic amps of the push-pull pair.

At higher frequencies, CBTF amps can be made much smaller using surface mount components because much smaller input, output, and feedback transformers are feasible at higher frequencies. For example, I have built a basic CBTF amp which is about 1 inch square to replace the 45 MHz 1st IF amp in my Drake R8 with ICP3in of about +30 dBm at 45 MHz and about 16 mA collestor current. The amp is a key ingredient in a mod which significantly improves the R8 dynamic range, and is described in my recent article, "Drake R8: Increased Dynamic Range, Mod 2," which should appear soon in DX News and DX Monitor. It is really not worth the effort to use surface mount components in the 100 KHz - 30 MHz amp described above because the transformers, chokes, and BJT's take up most of the space.

Another application of CBTF amps, already mentioned above, is to broadband phased wire antenna systems. As pointed out above, Victor Misek's phasing circuit is greatly improved when the original power FET amp is replaced with a push-pull CBTF amp. Other phasing approaches which require amps, such as Gerry Thomas' (1985 DX News) "Phase One" delay line circuit (adapted from John Webb's SW circuit described in Oct. 1982 QST, and recently revived by Mark Connelly in his article, "DL-1 Delay Line Phasing Unit," DX News, Vol. 61, No. 26, May 23, 1994), may also provide much improved performance when a push-pull CBTF amp is used. Mark recommended against using an amplifier with a delay line phasing circuit in a high RF urban environment, and mentioned amplifier outputs of +20 dBm for strong local stations. But such high outputs are impossible with a 12 dB gain push-pull CBTF amp, reasonable length wire antennas (say, 100 feet long or less), and a phasing circuit (which introduces loss), assuming that the listening location is a reasonable distance away

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from a 50 KW transmitting tower. I'd say that if you have -10 dBm on your antenna, then either your antenna is too long, or you live too close to the transmitting tower. My 1 KW super-local KRUS puts about -21 dBm on my wire antennas, so that with a 12 dB gain amp, I am looking at about -9 dBm. However, I would not use the 12 dB gain amp unless I had about 12 dB loss in my phasing system. Broadband amps, even ultralinear broadband amps, should only provide enough gain to make up loss, no more. The correct way to use a broadband amp with a phasing circuit is to use a resistive attenuator ahead of the amp with the attenuation selected to exactly equalize signal throughput, i.e., the amp and phasing system combined should have 0 dB gain, or at most 1 or 2 dB gain to overcome any additional noise introduced by the amp.

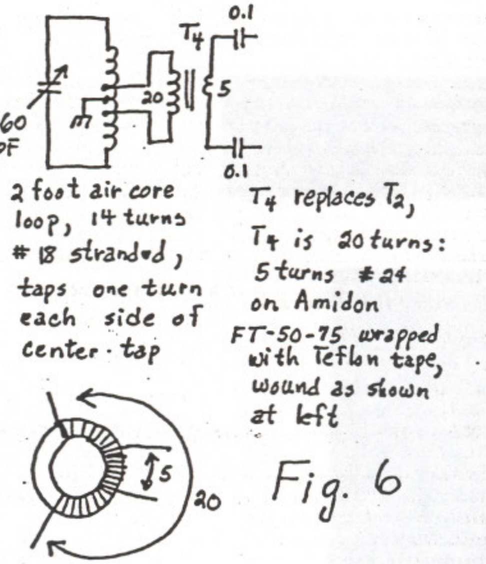

Fig. 6

An application which I intend to try next fall when noise levels drop is a push-pull CBTF amp running at reduced collector current with my two foot air core loop. This potential application was discussed above; cf. Fig. 3(d) and associated remarks. An interface of a push-pull CBTF amp with a two foot balanced air core loop is given at left in Fig. 6. After recent experiences with IMD3 in 50 to 2000 ohm transformers for impedance matching mechanical filters, I am not so sure that the FT-50-75 ferrite toroid specified in Fig. 6 has sufficient cross sectional area to prevent IMD3 originating in the transformer from degrading performance. An FT-114-75 or larger may be required for this application. In fact, to be certain that transformed IMD does not dominate system IMD, ferrite material transformers should not be used at all, but rather large cross sectional area powdered iron transformers. A T-106-15 with 120:30 turns of #30 enameled copper wire should probably be used, but it is such a hassle to wind.

Adding a tuned, push-pull, CBTF amp ahead of a receiver is, without a doubt, the most effective means of substantially increasing the 2nd order performance and wide-spaced 3rd order performance of a receiver. For example, a tuned, MW, 9.5 dB gain CBTF amp followed by a 4 dB attenuator, which will be described below, improved an NRD-525 intercepts by the amounts given in Fig. 7 below.

Fig. 7

IMD	NRD-525	NRD-525 + tuned p-p CBTF amp
1500 - 990 = 510 KHz	+60 dBm (ICP2in)	greater than +100 dBm (ICP2in)
600 + 700 = 1300 KHz	+54 dBm (ICP2in)	greater than +100 dBm (ICP2in)
2x600 + 700 = 1900 KHz	+39 dBm (ICP3in)	greater than +50 dBm (ICP3in)

The measurements in Fig. 7 above were made with a parallel LC tuned circuit ahead of a 3:15:9 turn winding push-pull CBTF amp drawing 16 mA collector current for each basic amp of the push-pull pair, i.e., about 32 mA total current drain. The parallel LC tuned circuit was an Amidon FT-50-61 with 48 turns #28 enameled copper wire, tapped two turns from the bottom, with a two turn link for antenna input. The tap went directly to T2 of Fig. 2. If this apprach is used with receivers which have higher close-in ICP3in, such as the RACAL RA6790/GM, a large powdered iron toroid should be used; otherwise close-in ICP3in will be degraded. A T-106-15 with 71 turns #24, tapped 3 turns from the bottom, with a 3 turn link would be suitable. In both cases, a 660 pF air variable capacitor should be used (which provides a tuning range of about 500 to 2000 KHz. If a 660 pF air variable capacitor is not available, whatever is available (but at least 365 pF) may be used. Of course, the number of turns on the toroid will have to be increased if a lower value air variable capacitor is used. The ratio of about 20:1 for tap and link should be maintained for other turns ratios.

For a LW tuned, p-p, CBTF amp, 150 turns #32 on an FT-82-61 with 2 turn link and 2 turn tap gave excellent results. The tuning range was about 140 to 600 KHz with a 660 pF air core variable capacitor.

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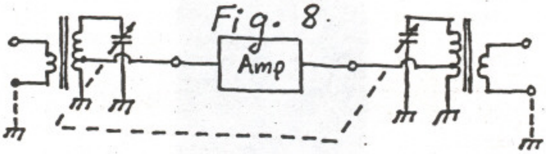
For a high SW band tuned, p-p, CBTF amp, 12 turns #24 on a T-50-2 with 2 turn tap and 2 turn link was excellent, and had a tuning range of about 4 to 25 MHz. A T-106-2 toroid would, perhaps, be a better choice to guarantee minimum IMD, but too few turns are available for proper impedance matching with a T-102-6.

A T-106-2 is suitable for a low SW band tuned, p-p, CBTF amp, but I seem to have lost my winding notes for a 1.7 to 10 MHz tuning range using a 660 pF air variable. Oh well, I am sure you get the idea.

Back to the LW tuned, p-p, CBTF amp, if you don't mind winding, and winding, and winding, you should probably give a T-184-3 a try. It is a hefty hunk of powdered iron about 1.84 inches outside diameter, weighing about 5.5 ounces. On the other hand, there probably isn't any point in going to that amount of "overkill," since signal levels in the VLF band generally are not high enough to cause close-in IMD3 problems.

The link-input-tap-output LC tuned circuits described above are merely the simplest way to implement tuned CBTF amps. A second LC tuned circuit may be added at the amp output as shown below in Fig. 8. More elaborate tuned circuits may also be used, such as capacitor coupled or inductor coupled double tuned circuits with either tap or link feed to the CBTF amp. A tuned CBTF amp using the circuit of Fig. 8 gave excellent performance with T-106-15 powdered iron toroids and a dual 550 pF air variable capacitor when used with a Drake R8. But I am not ready to commit myself to a particular implementation at this time.

Fig. 8



It should be emphasized that a tuned, p-p, CBTF amp will do nothing for close-in IMD3, and can even make matters worse if signal levels are raised too much with too much gain. You local RF environment will determine how much gain ahead of your receiver can be tolerated before your receiver begins to complain. And your receiver idiosyncracies will have a bearing on that issue. For example, a stock Drake R8 with no preamp available below 1.5 MHz can easily accept a 12 dB gain, tuned, p-p, CBTF amp. However, if you have modified you R8 as I have, with the original preamp replaced by a 9.5 dB gain, non-p-p, CBTF amp which can be activated below 1.5 MHz, then a 9.5 dB gain, tuned, p-p, CBTF amp followed by a 4 dB attenuator is a better choice. With such an arrangement, my (modified) R8 has higher wide-spaced ICP3in and higher ICP2in than either my R-390A or my NRD-525 (both with no tuned preamp). But if you bash a modified R8 with a 12 dB gain amp in the MW band with the R8 preamp turned on, the R8 performance will not be nearly as good.

The above approach should also be suitable for other receivers with broadband front ends, though the amount of amp gain and the amount of attenuation following the amp should be adjusted for the particular receiver and local RF environment.

For many DXers, a push-pull amp may not be necessary, and a single basic CBTF amp may be sufficient to eliminate wide-spaced IMD3 and IMD2. It will depend on the receiver and the local RF environment.

As I said at the beginning of these notes, the purpose of this article was to summarize my experiences with CBTF amps using 2N5109 and 2N3053 BJT's, and to provide other DXers enough information to construct and use these kinds of CBTF amps. In addition, I pointed out that a fertile area for further study may be non-standard turns ratios, which could lead to better two-way impedance match to Z_0. Also, little is known about how to interface CBTF amps with broadband active antennas, and with tuned active antennas. In both cases, CBTF amps should lead to improved performance. And also, a thorough and complete study of the relationships between maximum ICP2in and collector current, and between maximum ICP2in and frequency needs to be done for these kinds of CBTF amps. Finally, tuned CBTF amps should be developed to improve the 2nd order preformance and wide-spaced 3rd order performance of broadband-front-end solid state receivers, and to overcome the designed-in degraded sensitivity on some or all bands which plagues many solid state receivers.