

# **Complementary Push-Pull Amplifiers for Active Antennas: A Critical Review**

by

Chris Trask / N7ZWY  
Sonoran Radio Research  
P.O. Box 25240  
Tempe, AZ 85285-5240

Senior Member IEEE

Email: [christrask@earthlink.net](mailto:christrask@earthlink.net)  
20 February 2008  
Revised 10 June 2008  
Revised 2 December 2008  
Revised 4 July 2013  
Revised 15 September 2013

## Introduction

Active antennas generally require amplifiers of exceptional intermodulation distortion (IMD) performance, as well as good noise figure (NF) performance coupled with sufficient gain to at least overcome transmission line losses to the receiver. IMD performance becomes increasingly important as one ventures downward into the HF and then the MF and LF broadcast band spectrum, whereas there is less emphasis in NF performance as terrestrial and galactic background noise dominates the noise environment and renders good NF performance in receiver front ends as being a secondary design goal.

Many designs exist for active antenna amplifiers, and the majority of them suffer from poor IMD performance but are still useful for general purposes. More demanding users properly see good IMD and NF performance as being essential characteristics in an antenna/receiver system, and spare little expense in the pursuit of good equipment.

There is a great deal of interest in active antennas that make use of small antenna elements, such as short verticals and dipoles as well as ferrite-cored magnetic field loop antennas and electric field loops. The amplifiers associated with these antennas must not only have exceptional IMD performance and good NF performance, but should also be affordable and make use of components that are readily available worldwide.

One approach to the design of such amplifiers makes use of a MOSFET or JFET device operating as a source follower as the first stage to provide a high impedance for the electrically small antenna element. Such a stage is then followed by a second stage that couples the signal to the low 50- or 75-ohm load impedance of coaxial cable, preferably with some gain but most certainly without signal level loss. A suitable choice for the second stage is

an emitter follower, which will easily accommodate the low cable load impedance while providing a fairly high load impedance for the source follower first stage. Although such designs do not offer any signal gain, they are capable of very high IMD performance, which can be an acceptable trade-off.

## The KAA 1000 Amplifier

The origins of this series of active antenna amplifiers goes back at least to a Warsaw Pact active monopole antenna known as the KAA 1000 (1). Shown in functional form in the schematic of Fig. 1, this amplifier uses a single-gate MOSFET as the input device, biased at a fairly high current of 48mA. The potentiometer R2 is adjusted as part of a test procedure described in the manual. The inductor L1 provides a high signal impedance to the MOSFET source.

The complementary output transistors are operated in class AB with a collector current of 5mA, which is adjusted by varying potentiometer R6, again as part of the test procedure. Diodes D1 and D2 provide bias stabilization over the specified temperature range of -25°C to +80°C.

Resistors R8 and R9 provide additional bias stabilization, and resistor R10 aids in providing a source impedance to the 75-ohm cable. Not shown in Fig. 1 is a large inductor used to pass the supply power from the cable to the Vcc line of the amplifier. Current drain for the KAA 1000 is specified as being less than 100mA.

The design of the KAA 1000 is, of course, somewhat dated, however is very informative in terms of concept and execution. Single-gate MOSFETs for small-signal applications pretty much faded away after the RCA 40673 went out of production due to RCA selling off all of their semiconductor fabrication facilities almost three decades ago.

It is difficult to comprehend why anyone would resort to using class AB in a small signal application, especially in an active antenna amplifier where exceptional linearity and NF are highly desired. Such a topology is usually relegated to power amplifiers where power efficiency and linearity are simultaneous design goals. The designer of this unit had gone to considerable trouble to provide for good performance by heavily biasing the MOSFET and stabilizing the biasing over temperature, and then spoiled it by not using class A in the output stage.

As it stands, the KAA 1000 has a third-order output intermodulation point (OIP3) of under +30dBm (into 75 ohms), and the three resistors R8, R9, and R10 actually degrade the gain of the unit.

### The Lankford Complementary Push-Pull Amplifier

A recent adaptation of the KAA 1000 with improved IMD performance was devised by

Dallas Lankford (2), the functional schematic of which is shown in Fig. 2. Here, the MOSFET has been replaced by a more contemporary JFET, the biasing of which is adjusted by potentiometer R2. The two output transistors are biased as class A, and this combination provides an excellent degree of linearity, the OIP3 being in the vicinity of +50dBm.

The overall design does have one serious shortcoming, which is the low load impedance seen by the JFET due to the lack of a suitable inductor in series with the 180-ohm resistor R4. This results in a gain loss of approximately 3.5dB, which detracts from the potential NF of the circuit and the overall signal-to-noise (SNR) performance of the receiver system.

Also impairing the circuit is the lack of temperature compensation diodes in the bias string for the output transistors (R5, R6, and R7). Just as the diodes in the KAA 1000 are essential for maintaining the class AB bias point over temperature, they are equally important in main-

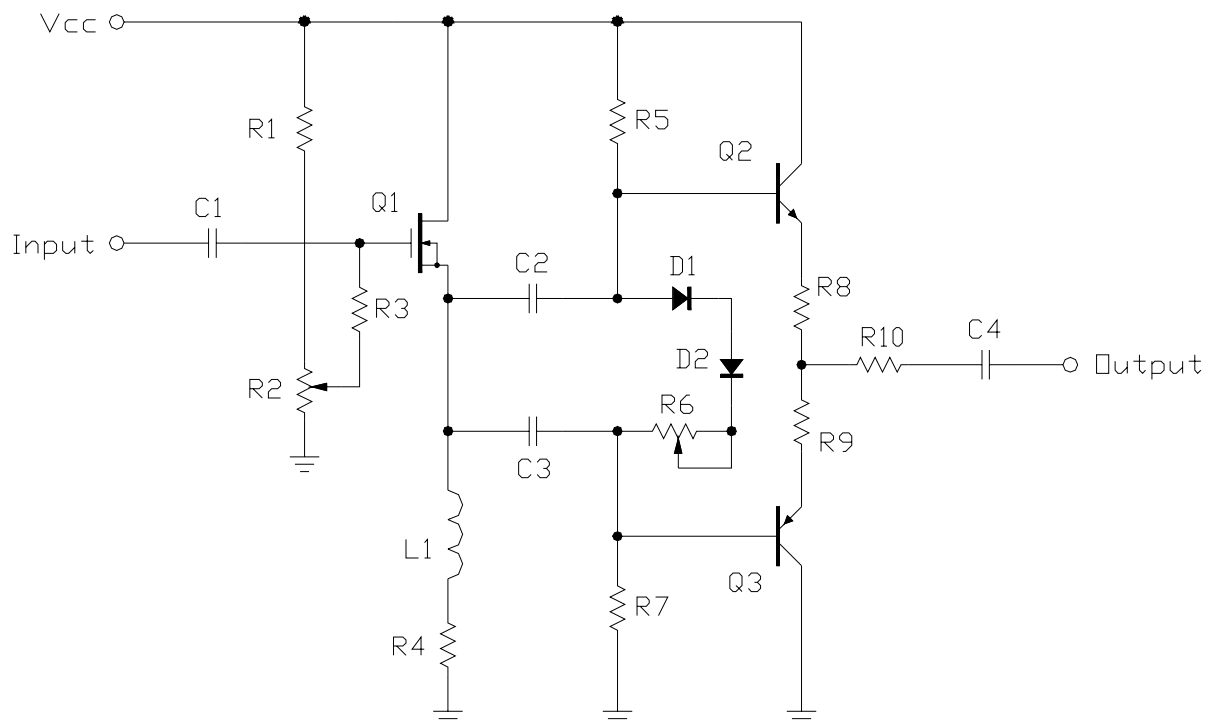


Fig. 1 - KA 1000 Complementary Push-Pull Active Whip Antenna (from Reference 1)

taining the bias point of class A amplifiers that operate at appreciable collector currents.

A serious inconvenience exists with the PNP output transistor, which is a 2N5160. Despite its good linearity performance (see Fig. 3), the device has been rendered obsolete as a consequence of the availability of better performing and less expensive devices, as well as the fact that very few designers consider PNP devices in RF design due to the overall lack of suitable devices plus the overriding prejudice towards designs that incorporate only NPN devices.

As it is, the 2N5160 is currently only available from Microsemi, as part of its ever-growing line of replacement semiconductors. That product line grew substantially a few decades ago when Motorola suddenly decided that it was no longer going to be a participant in the discrete semiconductor market. The 2N5160 now costs around \$US10 each in small quantities, and will likely increase as the demand for replacement devices such as this naturally de-

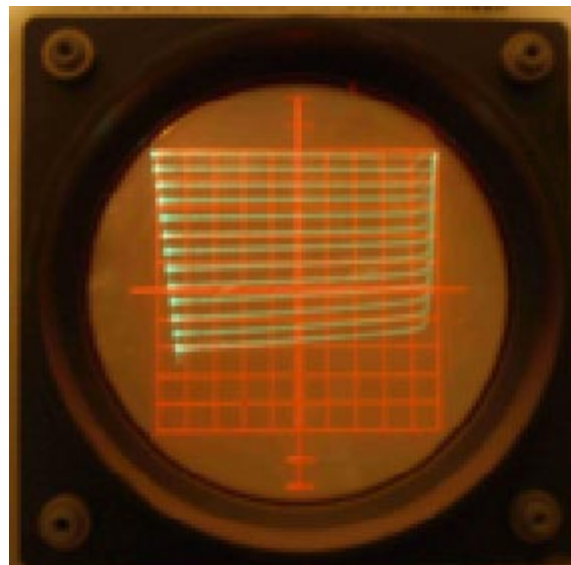


Fig. 3 - 2N5160 Characteristic Curves (horizontal 1V/div, vertical 2mA/div, 20μA/step)

creases with time.

### A Pair of Updated Complementary Push-Pull Amplifier Designs

Both of the circuits discussed thus far

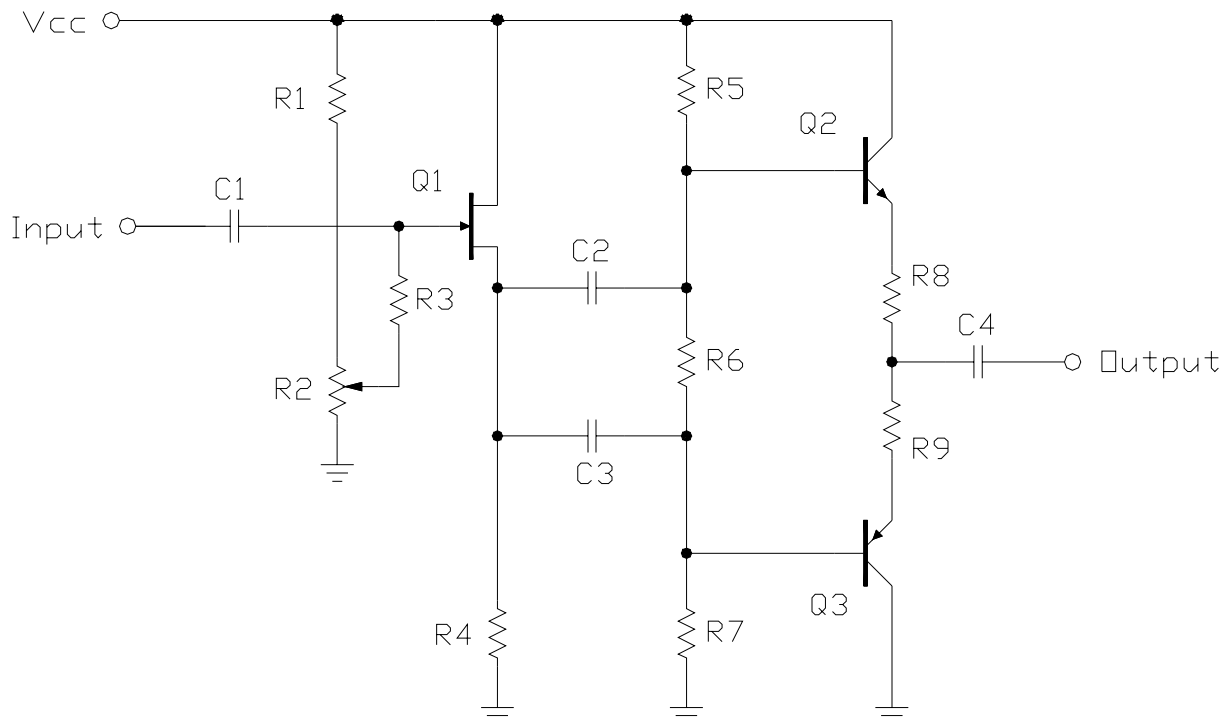


Fig. 2 - Complementary Push-Pull Active Whip Antenna as Designed by Dallas Lankford (from Reference 2)

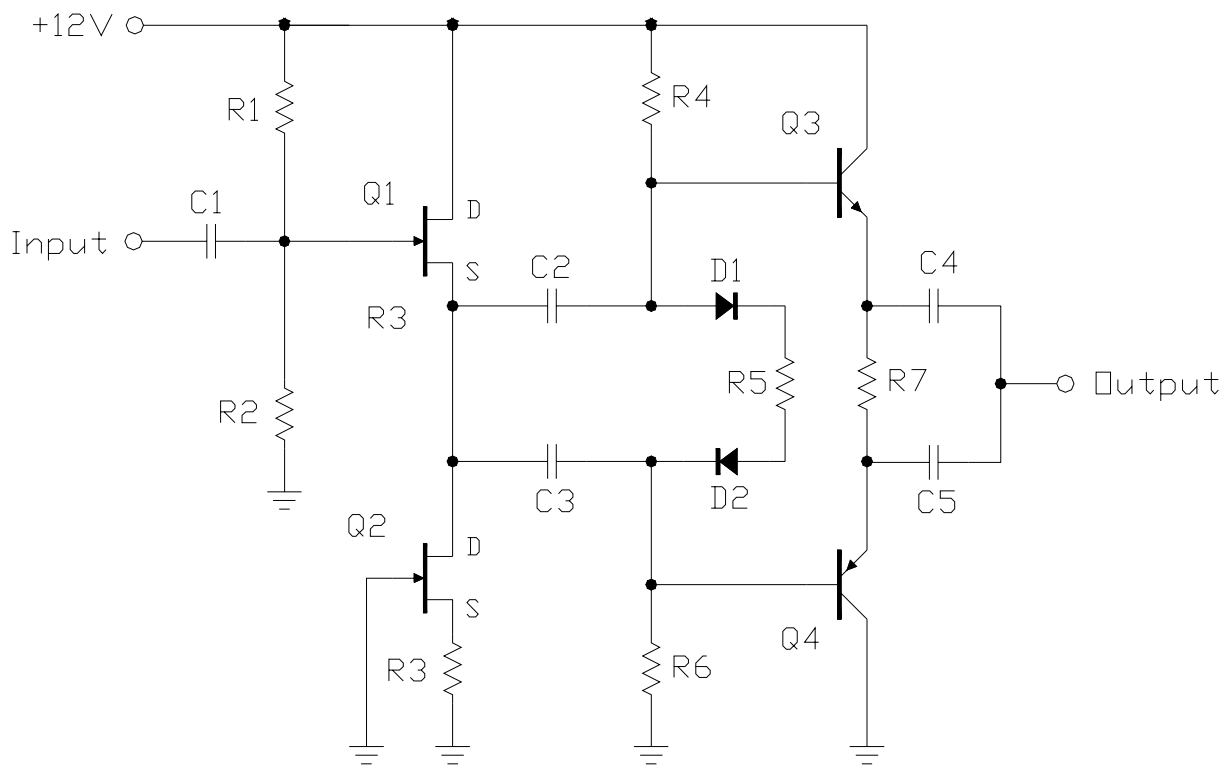
have both positive and negative points. One positive aspect that they have in common is the use of a MOSFET or JFET source follower in the first stage so as to provide a high input impedance. Another is the use of a complementary pair push-pull output stage.

The KAA 1000 uses a high value inductor in the source load to avoid signal level loss whereas the Lankford design omits this component and subsequently has a moderate loss in signal gain, impacting both NF and SNR, which are important considerations in the de-

sign of receiver systems.

The Lankford design uses a class A bias level in the output stage, while the KAA 1000 uses class AB, which results in significantly lower IMD performance. However, the Lankford design omits the thermal compensation diodes of the KAA 1000, even though both designs require them, each for their own reasons.

Lastly, there is the nagging inconvenience of the cost and availability of the 2N5160 transistor.



#### Parts List

C1, C2, C3, C4, C5 - 0.1 $\mu$ F

D1, D2 - 1N914 or 1N4148

Q1 - J309, J310, or U310

Q2 - J309

Q3 - 2N2222, 2N4401, MPS6521, or BFQ19  
(see text)

Q4 - 2N2907, 2N4403, MPS6523, or  
BFQ149 (see text)

R1, R2 - 1.0M

R3 - 120 ohms

R4, R6 - 10K

R5 - 3.3K (estimated)

R7 - 22 ohms

Fig. 4 - Complementary Push-Pull Amplifier with Single-ended Input Stage

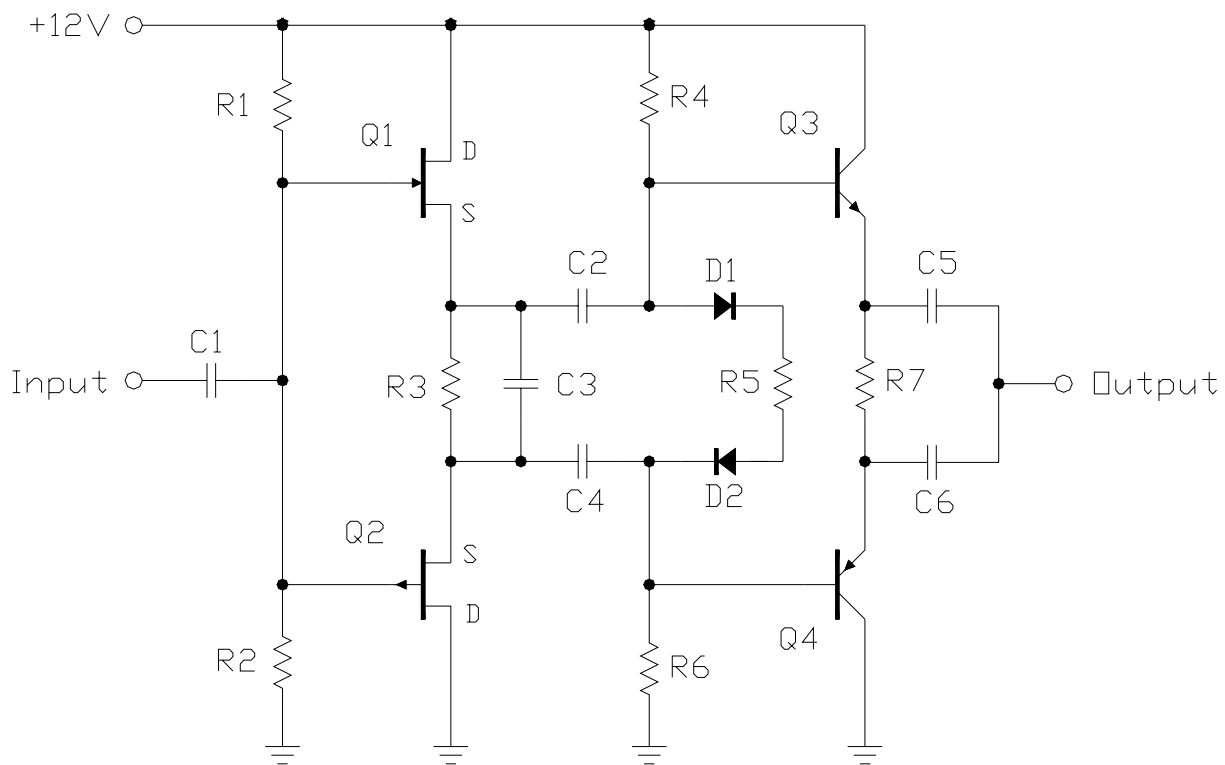
The positive points of these two designs can be synergetically combined and, with a little further modification be improved upon to render a design that provides the needed IMD and NF performance while at the same time using parts that are readily available from commercial distributors.

The first of these circuits is shown in Fig. 4. Here, the source load inductor of the KAA 1000 has been replaced with a JFET constant current source (Q2), where resistor R3 determines the bias current for the JFET source fol-

lower (Q1). This active load provides a very high load impedance for the Q1 source follower, which in turn results in better IMD performance of the input stage.

The temperature compensation diodes of the KAA 1000 have been reinstated (D1 and D2), and the output transistors Q3 and Q4 are biased class A so as to provide the highly desirable IMD performance similar to that of the Lankford circuit.

A variety of transistors are available for



### Parts List

C1, C2, C3, C4, C5, C6 - 0.1uF

D1, D2 - 1N914 or 1N4148

Q1 - J309, J310, or U310

Q2 - J174, J270, or J271 (preferred)

Q3 - 2N2222, 2N4401, MPS6521, or BFQ19  
(see text)

Q4 - 2N2907, 2N4403, MPS6523, or  
BFQ149 (see text)

R1, R2 - 1.0M

R3 - 100 ohms

R4, R6 - 10K

R5 - 3.3K (estimated)

R7 - 22 ohms

Fig. 5 - Complementary Push-Pull Amplifier with Complementary Push-Pull Input Stage

the output stage, and surprisingly the complementary pair of 2N2222 and 2N2907 delivers an OIP3 of +39.75dBm and an OIP2 of +59.5dBm with 50mA of bias current. Signal gain is -0.68dB, which agrees with PSpice simulations.

The MPS2222 and MPS2907 are equivalent to the 2N2222 and 2N2907 used for these tests. The MPS6521 and MPS6523 can give higher IMD performance due to their higher current gain, and the BFQ19 and BFQ149 can be biased to higher current levels to give even higher IMD performance. These devices are all readily available from distributors such as Mouser, where the MPS2222 and MPS2907 are less than \$US0.10 each and the BFQ19 and BFQ149 are available for less than \$US1.00 in quantities of ten or more.

The output of this amplifier is modified by using a single resistor between the emitters of the output transistors, and a pair of capacitors is used to couple the output to the coaxial cable. DC power may be provided through the cable by way of a large inductor, such as was done in the KAA 1000, or a simple 1:1 wide-band transformer.

A second circuit is shown in Fig. 5, where the active load in the circuit of Fig. 3 is replaced with a complementary depletion mode P-channel JFET (J271 preferred), so that the two input JFETs are complementary dynamic loads. Make careful note that the drain of the P-channel JFET is connected to ground.

The bias current for this stage is controlled by resistor R3. Capacitor C3 couples the two JFET sources together. All other aspects of this circuit are identical to those of Fig. 3.

### Prototype Construction and Testing

Prototypes of the circuits of Fig. 4 and Fig. 5 were constructed on Ivan board (0.80"

squares, 0.10" apart on 1/16" G-10 epoxy fiberglass, similar to FR-4), as shown in the photographs of Fig. 6. For the circuit of Fig. 4, the 3dB bandwidth is 30kHz to 74MHz and the gain is -0.68dB. IMD measurements show the OIP3 and OIP2 to be +39.75dBm and +59.5dBm, respectively. For the circuit of Fig. 5, the 3dB bandwidth is 30kHz to 91MHz and the gain is -0.68dB. IMD measurements show the OIP3 and OIP2 to be +44.25dBm and +68.5dBm, respectively.

The IMD performance of these two circuits is suitable for active amplifier applications and can be further improved by way of using higher current devices such as the BFQ19 and BFQ149 for the output devices, while the gain and NF are both improved upon over that of the Lankford circuit. Both circuits both make use of readily available components, and even if the more expensive BFQ19 and BFQ149 transistors are used, the parts cost is still less than \$US4.00.

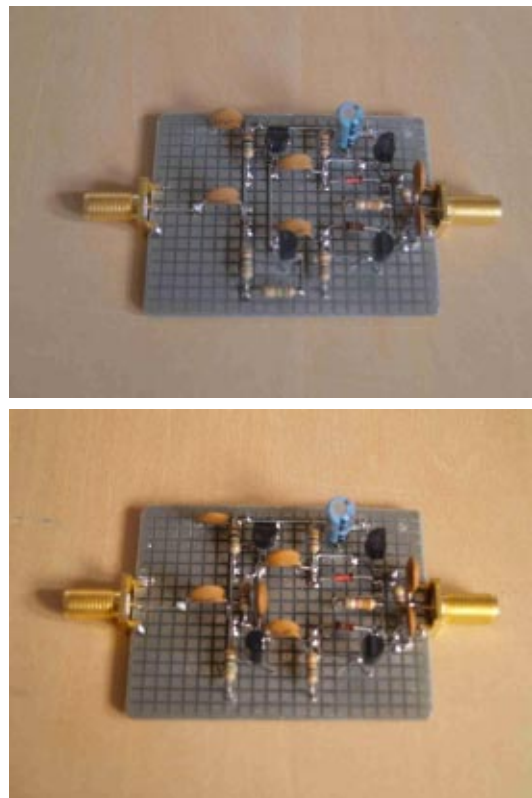


Fig. 6 - Prototypes for Circuits of Fig. 4 (top) and Fig. 5 (bottom)

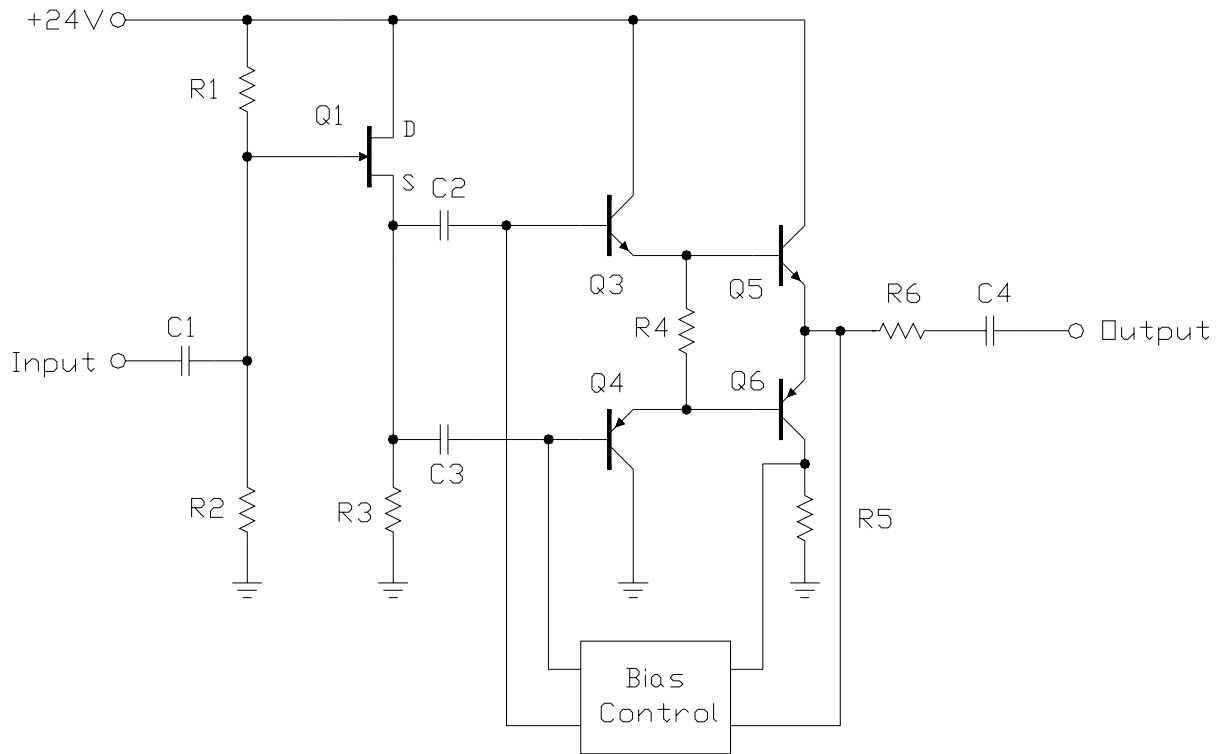


Fig. 7 - HE010 Active Rod Antenna Amplifier

### The HE010 Active Rod Antenna Amplifier

An interesting active antenna amplifier worth considering is the HE010 Active Rod Antenna manufactured by Rohde & Schwarz (3). Shown in block diagram form in Fig. 7, the amplifier consists of a single-ended JFET input stage similar to that of the KAA 1000, and

a push-pull Darlington output stage, which provides better linearity by way. Biasing control circuitry is also included that maintains a controlled output stage biasing current over temperature. Overall, this is a high-quality product, but the push-pull Darlington configuration of the output stage combined with the current sensing resistor R5 negatively impacts the dynamic range of the output stage.

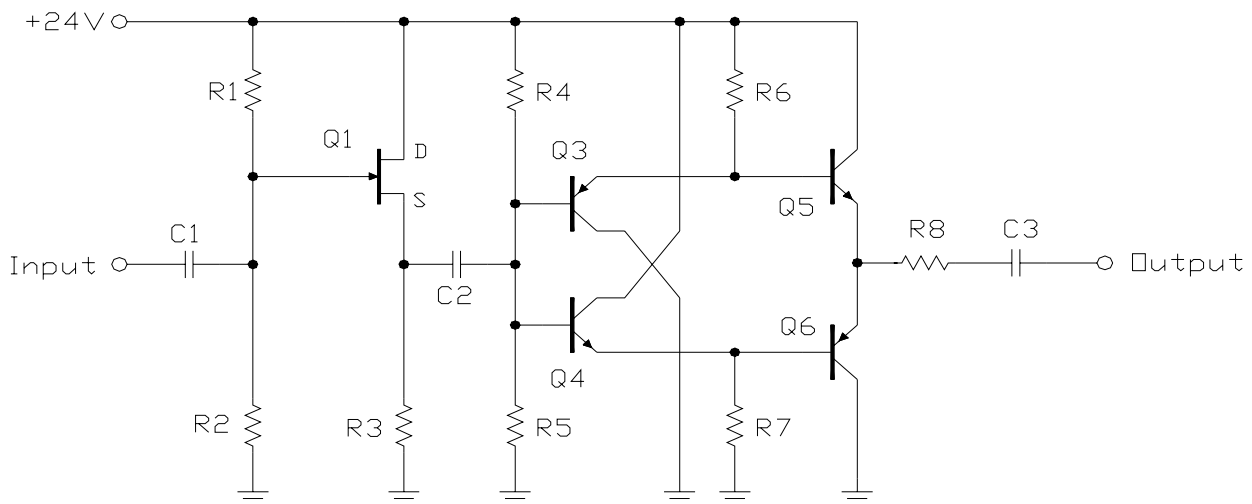
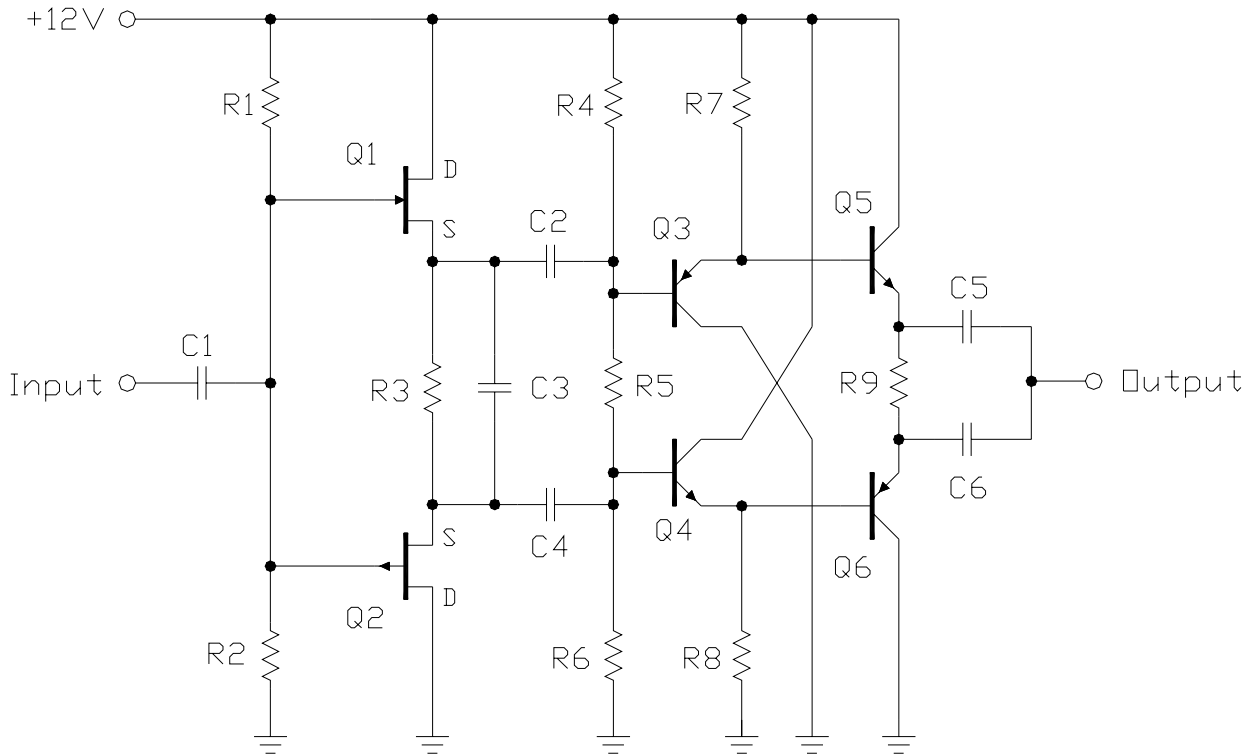


Fig. 8 - Modified HE010 Active Rod Antenna Amplifier





### Parts List

C1, C2, C3, C4, C5, C6 - 0.1uF	Q6 - 2N2907, 2N4403, MPS6523, or BFQ149 (see text)
Q1 - J309, J310 (preferred), or U310	R1, R2 - 1.0M
Q2 - J174, J270, or J271 (preferred)	R3 - 100 ohms
Q3 - 2N2222, 2N4401, or MPS6521 (preferred)	R4, R6 - 100K
Q4 - 2N2907, 2N4403, or MPS6523 (preferred)	R5 - 2.2K (estimated)
Q5 - 2N2222, 2N4401, MPS6521, or BFQ19 (see text)	R7, R8 - 470 ohms
	R9 - 10 ohms

Fig. 9 - Practical Adaptation of the Modified HE010 Active Rod Antenna Amplifier

This shortcoming can be remedied by employing complementary Darlington pairs in the output stage, as shown in Fig. 8. Comparing this amplifier with those of Fig. 4 and Fig. 5, the intermediate stage transistors Q3 and Q4 replace the temperature compensating diodes D1 and D2, retaining the desirable temperature compensation scheme and at the same time retaining the higher gain and hence better linearity as with the HE010. In addition, the dynamic range of the output stage is increased beyond that of the amplifiers of Fig. 4 and Fig. 5

by way of the DC voltage drop across the base-emitter junctions of Q3 and Q4, which allows the signal voltages driving the base terminals of output transistors Q5 and Q6 to approach closer to the supply rail and ground, respectively.

Another commercial product, the Clifton Laboratories Z1501D, employs a configuration similar to that of Fig. 8, using a single-ended intermediate stage in place of the complementary pair Q3/Q4 (4).

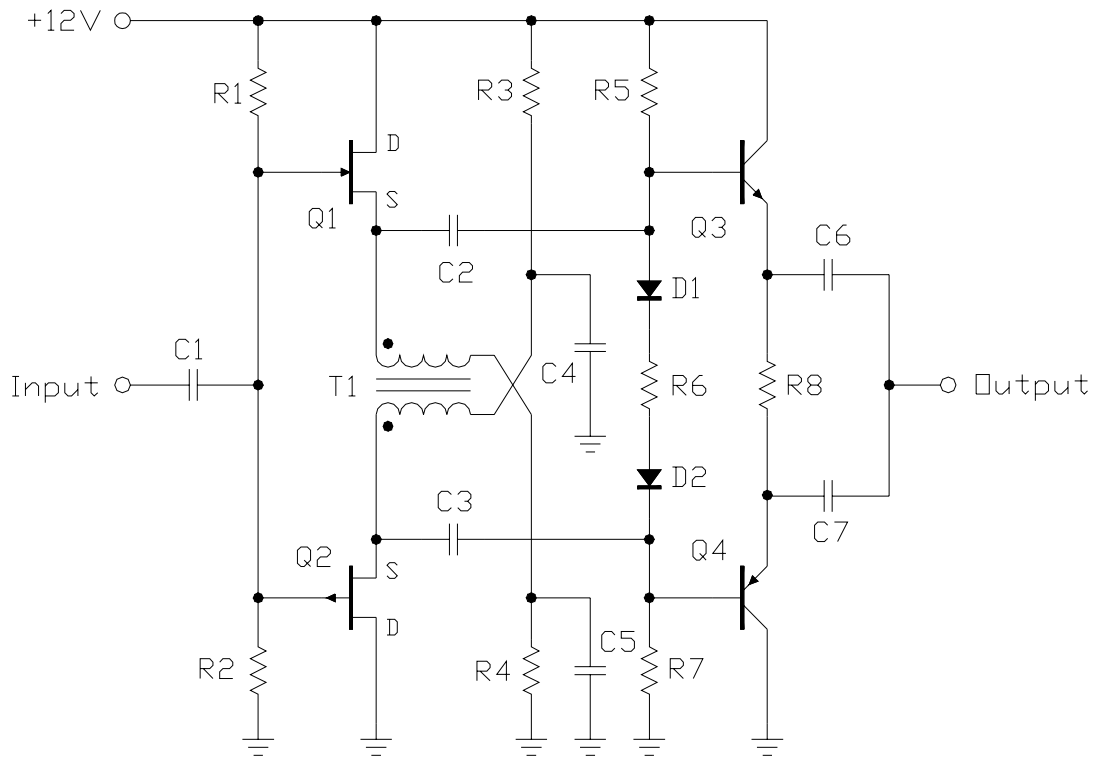


Fig. 10 - Complementary Push-Pull Amplifier with Complementary Push-Pull Input Stage and Independent Biasing

### Biasing Improvements

A number of builders have encountered difficulties with the complementary JFET input stage of Fig. 5. First, if higher biasing currents are desired the biasing feedback resistor R3 diminishes to zero, often before the desired biasing current is achieved. Second, some improvement in IMD performance can be obtained if the biasing currents of JFETS Q1 and Q2 are independent. These circumstances can be remedied by using separate biasing resistors for the two JFETS, but they are generally small in value and result in adverse loading of the JFET sources, which results in degraded IMD performance.

As shown in Fig. 10, adding a two-winding 1:1 wideband transformer allows for this biasing arrangement without degrading the IMD performance of the input stage. The values for resistors R3 and R4 are in the range of 330 to 820 ohms. The remaining parts values are similar to those of Fig. 5.

### Even-Order Distortion Improvements

The purpose of adjusting the biasing of the JFET input stage has been primarily to improve the IMD performance, specifically to reduce the second harmonic and even-order IMD products. Although this can be done to some degree of satisfaction by way of adjusting R3 and R4 in Fig. 10, the improvement can deteriorate over temperature and frequency.

Since the reduction of even-order distortion products is a result of having both JFET transistors develop equal and opposite distortion products, a more general solution would be to detect the imbalance between the two devices and use a negative feedback loop to automatically reduce them.

Referring to Fig. 11, a 1:1 transformer T2 is added to the circuit of Fig. 10, through which pass the drain currents of Q1 and Q2. By connecting the two windings in reverse signal

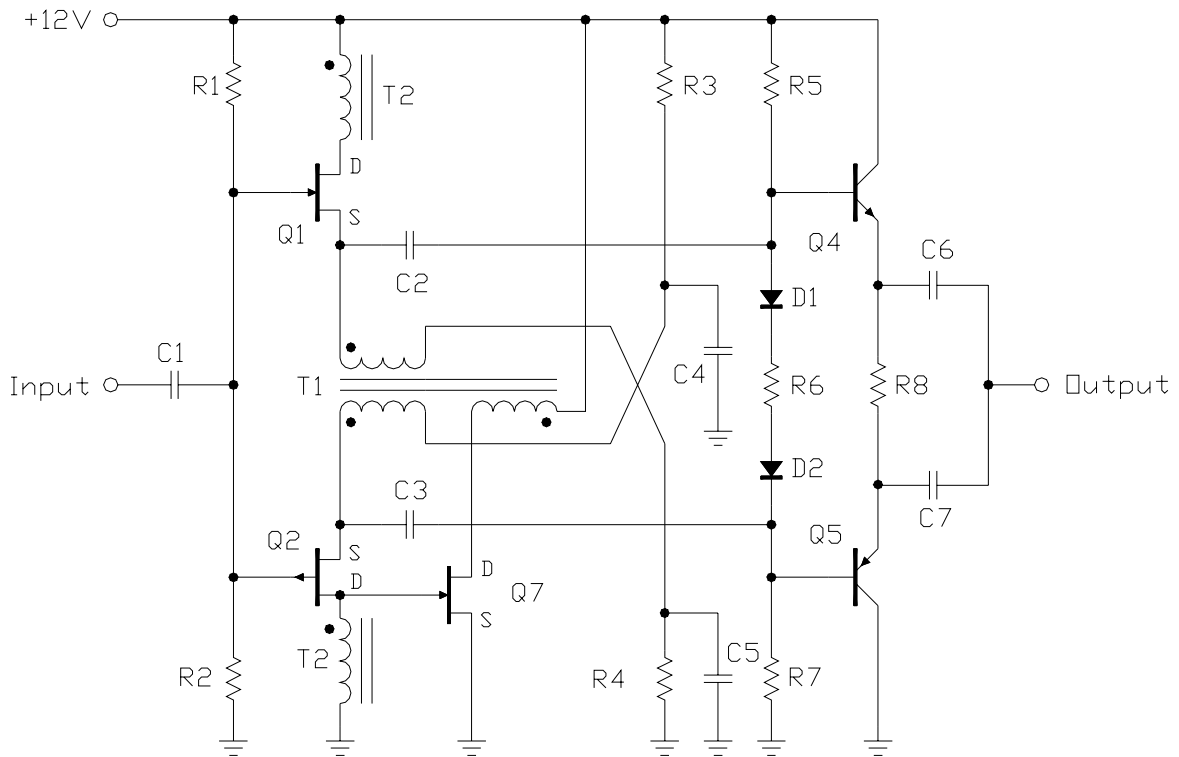


Fig. 11 - Complementary Push-Pull Amplifier with Complementary Push-Pull Input Stage, Independent Biasing, and Even-Order Distortion Feedback

sense, the difference between the signal currents of Q1 and Q2 will result in a difference signal voltage at the gate of the added JFET Q7. When in proper balance, the signal and odd-order distortion products will cancel and the even-order distortion products will be summed, resulting in an error signal.

The negative feedback loop is easily completed by adding a third winding to transformer

T1 of fig. 10. Now, the amplified error signal is coupled to the sources of JFETs Q1 and Q2, resulting in a substantial improvement in the balance of the two devices and a subsequent reduction in the even-order distortion products conducted to the output stage.

The push-pull complementary Darlington output stage of Fig. 9 can be added to Fig. 11, and the full circuit is shown in Fig. 12.

## References

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4. Smith, Jack, *Z1501D Active Antenna Instruction Manual* (revised), Clifton Laboratories, Clifton, Virginia, 8 September 2010.

