Adding AGC to a Termination Insensitive Amplifier

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Update:

The term ***TIA*** as used in this report is something that appeared on the Internet after K3NHI and I presented our work in 2009. This should not be confused with the more common use of the *TIA* acronym, which stands for transimpedance amplifier. (A good discussion appears in Wikipedia.)

This report describes an amplifier where gain can be controlled by an applied voltage. This is offered as part of an AGC system. However, this is not a complete AGC system. The chore of detecting the signal to obtain a voltage that can be applied to the amplifier is left to the experimenter/builder.

My circuit design friend Bob Kopski, K3NHI, and I collaborated in an on-line paper in 2009 to investigate simple bipolar transistor amplifiers that were more load tolerant. (See references at the end of this note.) This Termination Insensitive Amplifier (**TIA**) investigation came about after we encountered problems with a published design using simple bidirectional feedback amplifiers. As the direction of signal flow through those circuits was changed, impedance levels changed, causing a connected crystal filter to see changing termination impedance values. This caused the filter response shape and bandwidth to change as the transceiver switched between transmit and receive. This was not a catastrophic problem, but it was nonetheless unsettling, for it impacted equipment performance.

The use of termination insensitive amplifiers improved transceiver performance, but left a need in receiver performance: Automatic gain control was desired. This article addresses this need.

Consider first the basic bipolar transistor version of a negative feedback amplifier, show below in Fig 1A. This circuit became popular in the early days of cable television systems and has become a long time favorite of mine. This circuit uses transformer coupling at the output, although this is not necessary. In normal applications, both the source and the load resistances are 50 ohms.

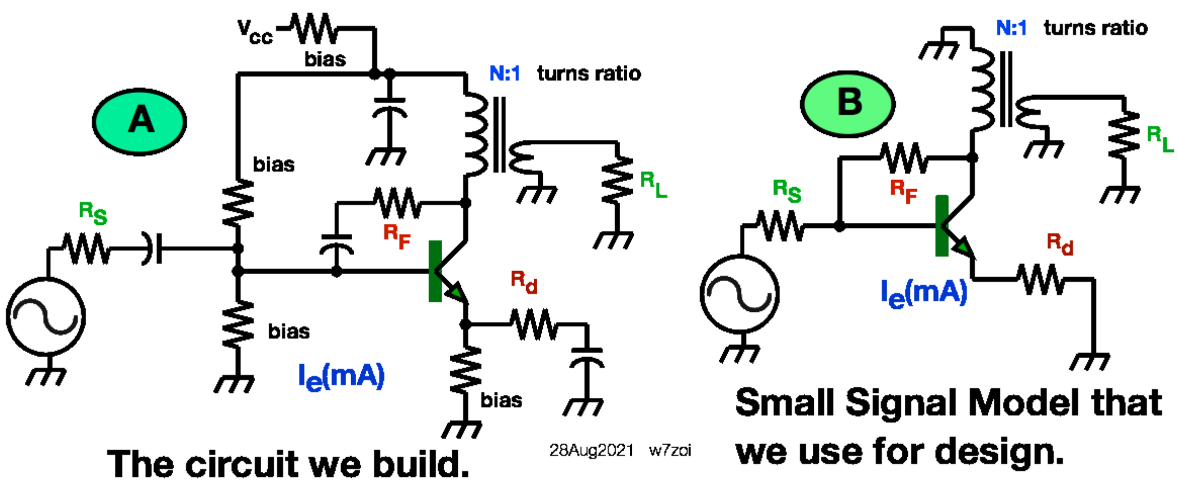


Fig 1. The basic feedback amplifier. Part A shows a practical circuit form while B presents a small signal model.

Two forms of the feedback amplifier (**FBA**) are shown in Fig. 1. The second, Fig 1B, is the one we use when thinking about possible circuit forms and the analysis necessary for design. Biasing details are removed in Fig 1B, leaving only the salient RF amplifier behavior. Two forms of negative feedback are present for radio frequencies. One is series feedback from the emitter degeneration provided by Rd. A common emitter amplifier **without degeneration** (Rd=0) would have a voltage gain of Gv=Rc/re where Rc is the load resistance at the collector and re is the intrinsic emitter resistance, approximately 27/Ie where Ie is now the emitter bias current in mA. For example, a transistor biased at 10 mA emitter current would have re=2.7 ohms. If the amplifier was loaded with 200 ohms, a result of a N=2 transformer turns ratio, the voltage gain (base to collector) would be 200/2.7=74. This high voltage gain is decreased when we add external degeneration with Rd. The voltage gain now becomes Gv=Rc/(re+Rd). If Rd = 10 ohms, the base to collector voltage gain is now 15.7. Lower voltage gain means that less base signal current is needed, so emitter degeneration **increases** input impedance.

The other negative feedback is parallel feedback provided by Rf connected from the collector to the base. The collector voltage is out of phase with the base RF voltage. The feedback from signal current flowing through Rf is low if Rf is high. However, as feedback resistance drops, gain drops. Assume a 1K value for Rf. The collector voltage is divided by Rf and the source resistance Rs (usually 50 ohms) to provide a small feedback voltage at the input. This out-of-phase component adds to the signal from the source. With 1K and 50 ohms for Rf and Rs, the signal appearing at the base is that at the collector divided by 20, the ratio of Rf to Rs. The result is reduced voltage gain. It also means that a larger base signal will be required to produce the base current that would have been needed before Rf was connected. Hence, the parallel feedback serves to **decrease** input impedance, just the opposite effect of emitter degeneration. Overall gain as well as the input and output impedance values can be controlled with the two feedback forms. A side benefit is improved circuit stability, freedom from self oscillation.

Alas, there is a price for this flexibility. That price is in termination sensitivity. If we change the output load resistance, the collector voltage will change for a given base drive and feedback resistance values. The voltage gain will change. A reduced gain means that more base current must flow to achieve a previous level of collector voltage, which means that the impedance looking into the base will have changed.

So, how do we modify the properties of a feedback amplifier to reduce this termination sensitivity? One solution is the addition of a second, cascaded stage, shown in Fig 2. The key to the improved performance is the use of a fixed, internal collector load resistance. Negative feedback of both forms is still used, but the parallel feedback now comes from a place in the circuit where the voltage no longer depends upon the load. The output buffer amplifier should have an input impedance that is much larger than the driving source impedance.

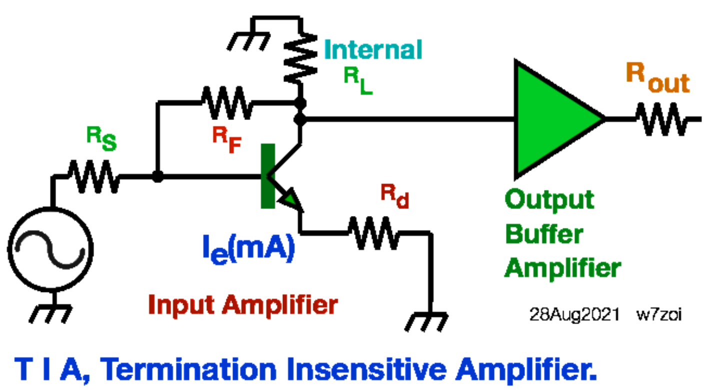


Fig 2. The original amplifier has its load replaced by a fixed resistor internal to the overall amplifier. The collector voltage is then applied to a buffer amplifier with unity voltage gain, but with a high input impedance that does not impact the new **internal** load resistance, **RL**. The buffer has a low output impedance that is brought up to 50 ohms with a series resistor.

What about gain control?

Amplifiers used in the IF stages of receivers often have gain that can be varied with a control voltage. These circuits are termed automatic gain control, or *AGC amplifiers*. They allow the user to reduce gain when a strong signal appears in the receiver output. The process is usually automated. The strong signal is detected to produce a DC voltage that can be amplified and applied to the IF amplifier to reduce the gain, keeping the output signal nearly constant. Alas, we can't easily modify the FBA described above to reduce the gain without altering other properties. Terminal impedance changes if feedback elements are changed. All FBA behavior depends more upon the value of the feedback elements than the open loop gain of the transistor. Changing, for example, the emitter degeneration will be change gain, but it will also change the input impedance, the very thing that we wish to maintain constant. There must be many solutions to the problem. One that seems reasonable is to add a third stage to the cascade between the TIA Input Amplifier and the TIA Output Buffer. This is shown in Fig 3.

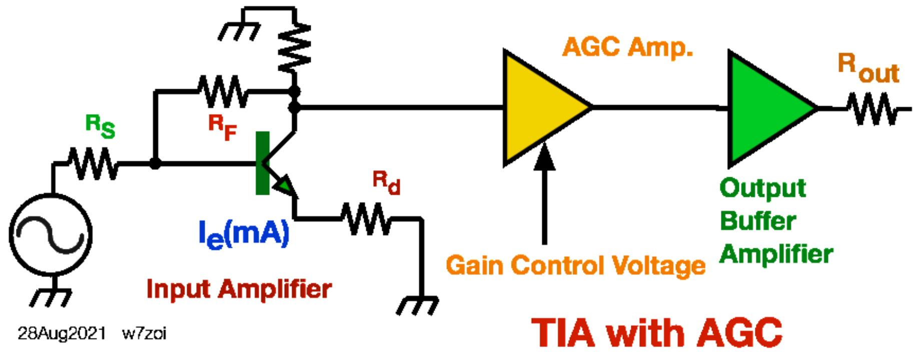


Fig 3. The TIA is modified by inserting a gain control stage between the two stages of the TIA presented in Fig 2.

An Experimental Amplifier

Figure 4 shows the start of an experimental amplifier with AGC. This is a practical implementation of the block diagram in Fig 2 above. The output buffer is a Darlington connected emitter follower with some extra emitter current in the first transistor. Fig 5 shows a photo of this circuit.

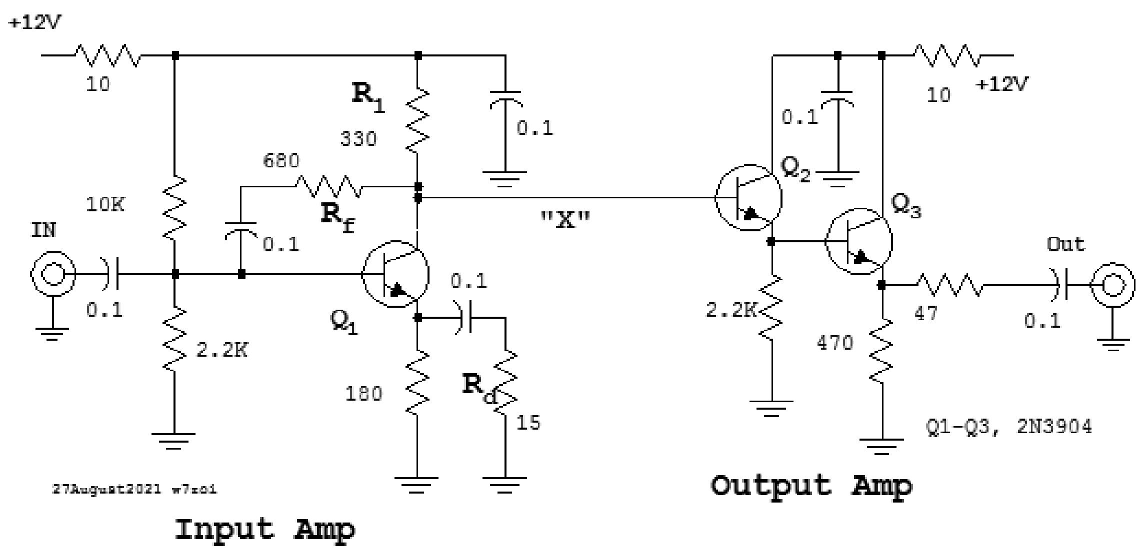


Fig 4. A simple termination insensitive amplifier. See the text for measurement results.

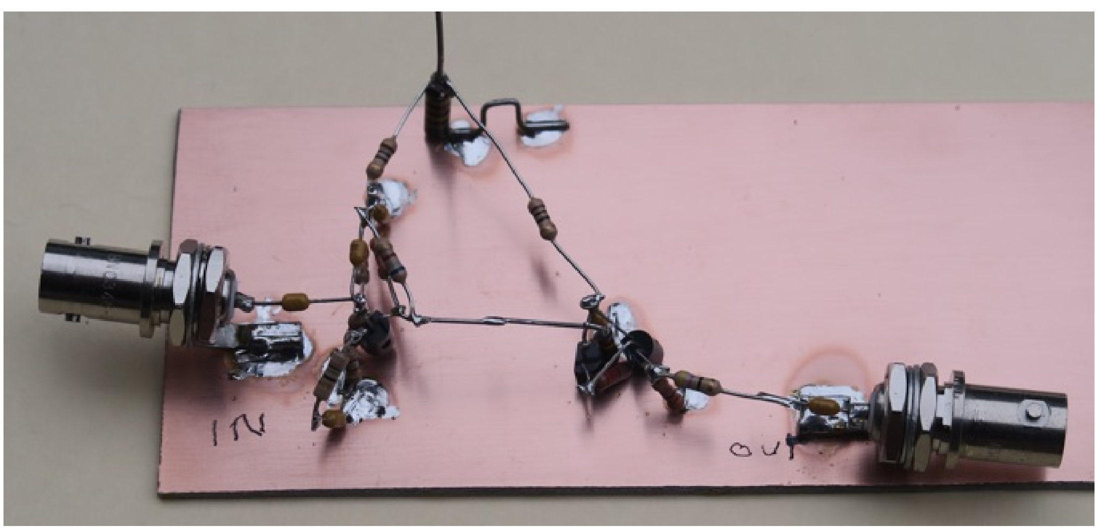
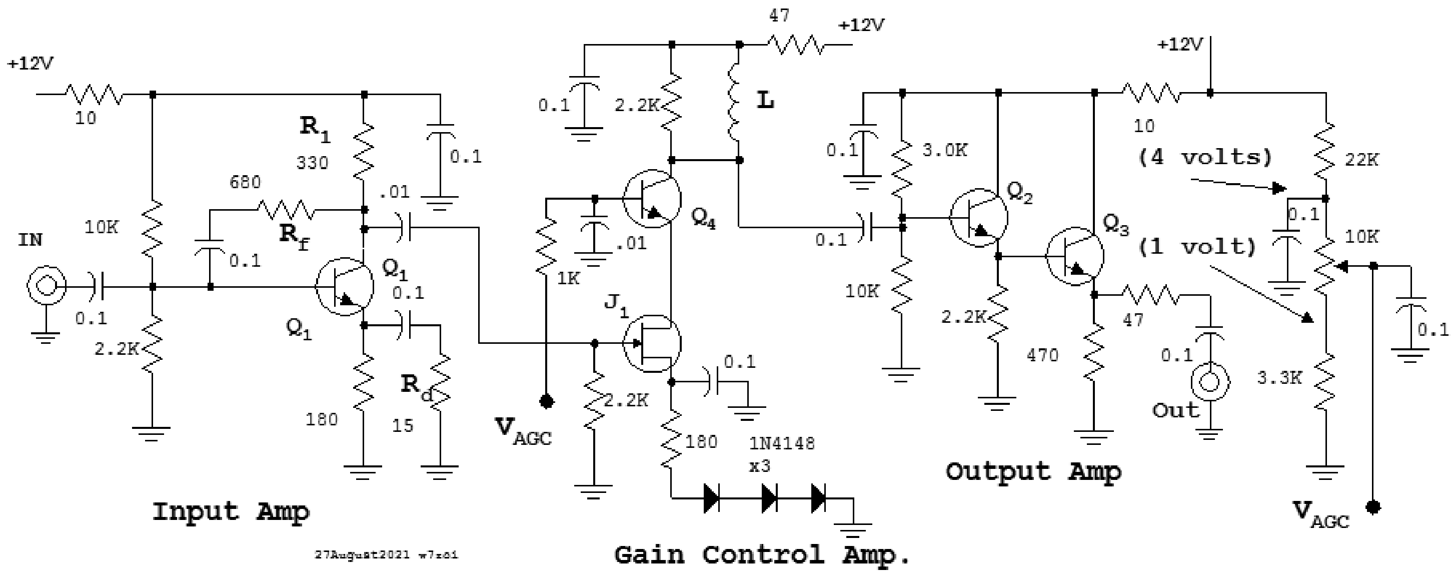


Fig 5. This is a photo of the breadboard for the circuit of Fig 4. BNC connectors were included for connection to test equipment. "***Ugly*** " ***construction*** was used to quickly build the circuit. Those unfamiliar with "*ugly construction*" can find

a description in a paper (The Ugly Weekender) that my younger son Roger, ka7exm, and I wrote for QST for August 1981. Also see the opening pages of Chapter 1 of **Experimental Methods in RF Design**, ARRL, 2003 (now out of print.)

We confined our measurements to one frequency of 10 MHz. The signal was supplied by a surplus HP-8654A signal generator. Signals were detected with a 50 ohm terminated Tektronix T922 oscilloscope. The terminated scope was preceded by a HP-355 C and D attenuator pair. The signal generator output was -30 dBm, low enough that the amplifier would not be driven into compression. The generator was attached directly to the attenuator/scope setup to provide a "through" calibration. The amplifier was then inserted in the signal path and the gain was found to be 15.5 dB, in line with earlier measurements. Next, the signal generator output was increased to -20 dBm and was attached to a homebrew return loss bridge. A 50 ohm terminator was temporarily attached, confirming that the bridge directivity exceeded 30 dB. The bridge was then attached to the amplifier input while the output was terminated in 50 ohms. The input return loss was 30.5 dB while the output was loaded with 50 ohms. Output return loss was 17 dB with the input 50 ohm terminated. Neither of these impedance match conditions changed when the 50 ohm load on the other port was removed, confirming that the circuit really is *termination insensitive*.

The next step is to add a gain controlled amplifier between the TIA input and the output buffer. The circuit is shown in fig 6. Figure 7 shows a photo of this setup.



Q1-Q4 = 2N3904 J1 = J310 L = 75 uH, 12t #28 on FB43-2401 or similar. L value is NOT critical.

Fig 6. A "HyCas" single stage circuit is inserted between the original amplifier stages. The 3.0K and 10K resistors at the input to Q2 bias the buffer at the same voltage that was present in Fig 5. Also included on the board is a pot that provides voltages from 1 to 4 volts, allowing the circuit to be tested. This IF scheme, the Hybrid Cascode, was described in a QST paper in December 2007, coauthored with Jeff Damm, WA7MLH.

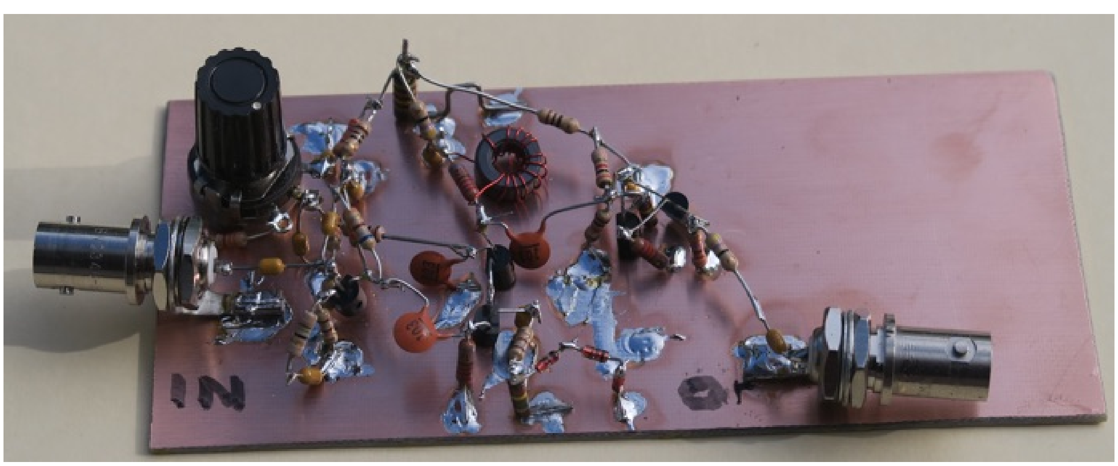


Fig 7. This is a photo of the modified amplifier, now including a gain controlled stage. A bit more room was needed for this stage, so the output buffer was moved further toward the output. This is easily realized with ugly construction.

The generator was again set for an output of -30 dBm. Small signal gain was 31 dB with the pot at maximum of 4 volts. The oscilloscope was replaced with a spectrum analyzer allowing a control range of 70 dB to be measured.

The return loss bridge was attached to the spectrum analyzer and driven with the generator at -30 dBm. The input return loss was 26 dB with the gain pot set at maximum, degrading to 23 dB at minimum gain. (By this point, the supply voltage for the J310 JFET was nearly zero.) The gain was reset to maximum and the input return loss was measured as the output load was removed. No change was seen. The output return loss was 17 dB for all gains and input terminations.

There must be many other ways to obtain TIA characteristics. The schemes presented used the familiar (and favorite) bipolar circuits with dirt cheap transistors. FET circuits offer promise, owing to their high input impedance. There is ample opportunity for the experimenter interested in circuit design at the component level.

Many builder/experimenters are interested in a bidirectional amplifier. This report deals only with half of such a design with the expansion to two directions left to the reader. Most applications will only require gain control on the receive path.

References: Click on the links to see the papers.

1. This paper shows several ways to get a TIA. http://w7zoi.net/bidirectional_matched_amplifier.pdf

2. This paper contains the mathematics behind the first one. http://w7zoi.net/fba_with_simple_model.pdf

3. This article expands on the models and includes some actual measurements.
http://w7zoi.net/transistor_models_and_the_fba.pdf

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