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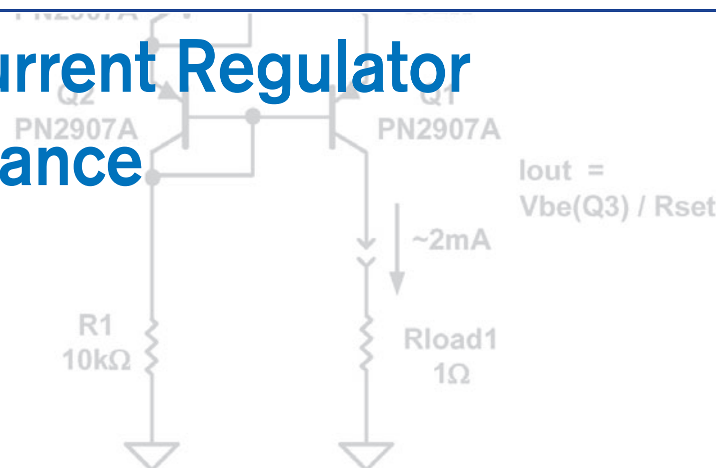
Sources 101: Audio Current Regulator Tests for High Performance

Part 1: Basics of Operation



Noted designer and author of a classic op-amp design cookbook begins his series on quieter power supplies.

By Walt Jung

This article deals with audio current regulator circuits and their performance with regard to power-supply-related noise. It describes a test methodology to characterize these audio current regulation elements and circuits for sensitivity to applied voltage. In terms of audio power supply circuitry within systems, this would be the *line rejection* or *impedance properties*. Because audio current regulators are often referred to as *current sources*, and the performance aspects of such for audio are basic, the article is logically entitled "Sources 101."

But, it isn't the last word on the topic by any means. I hope it can explain to many how to build better current regulator circuits for audio. And, most important, it definitely shows how to test these circuits, and to differentiate their performance.

THE WHYS AND WHEREFORES

While I have been fascinated by current regulators for years, it wasn't until recently that I investigated deeply the wideband AC performance of various topologies operating at many current levels. It was brought home to me that some greater insight could be useful, when a relatively simple "One Vbe" type of current regulator was found lacking, as operated within a shunt regulator design. That experience started this investigation several months ago, and the article here is one fruit of those explorations.

So, there we are. It may seem obvious that it is desirable to have audio circuits with high immunity to power supply potentials, but this area is seldom, if ever, addressed in audio design and construction articles. Typically, a current source or sink circuit is presented without related performance data, so it is difficult to differentiate what types of designs are better for audio. Some relatively simple power-supply rejection tests can help differentiate which circuits perform best and are most immune to power-supply-related distortions. This article details a wide variety of available current regulation circuitry, and documents their relative performance in terms of power supply immunity.

CURRENT REGULATOR PROPERTIES FOR AUDIO

Current regulators have several operating parameters that are key to audio circuit performance. Probably the most important is the *degree of regulation* of the associated current. In other words, the output current, Iout, is maintained at some fixed design level, one which is relatively independent of other circuit conditions. Thus, although the unregulated input voltage varies, the design current stays constant.

As noted, just how well this is done is one of the major figures of merit for a current regulator. You can detail the specification for this in several ways. One is simply the rejection (or line rejection) of noise appearing on the input, expressed most simply in dB, such as, for example, a rejection of 100dB. This means that input noise is reduced by 100dB (100,000/1), or it becomes –100dB with respect to the input (1/100,000).

Because audio is a wideband signal, it is important to quantify a regulator over at least the 20Hz–20kHz audio bandwidth, and preferably even wider. This is because these circuits often have a nonlinearity that can be excited with supersonic signals. This particular performance parameter is also expressed as *impedance*, which I will discuss further.

One form of nonlinearity often found in solid-state audio circuits is nonlinear capacitance. While a pure capacitance is not a distortion producer within an audio circuit, nonlinear capacitance can—and will—produce distortion, particularly when excited with high frequency (HF) noises, such as those typical to rectified-AC supply systems. So, one indirect figure of merit for audio current regulators is the associated capacitance. The lower this is, generally the lower will be any spurious responses to HF noise.

CURRENT *SOURCE* OR CURRENT *SINK*?

One point of potential confusion regarding current regulators for use within audio circuits lies with the terminology used. Two terms you often see are *current source* and *current sink*. These terms are often used interchangeably, but this isn't always technically correct. Some review of the terminology is helpful.

A current *source* circuit is a device (or more complex circuit) that provides current regulation properties, typically operating between a positive rail voltage and common (ground), often using one or more PNP transistors, so as to *source* load current. This is the more popular usage. However, you should note that current regulator circuits operating between a negative rail and common are also sometimes called current "sources."

Regardless of this definition muddling, it is more accurate to describe such circuits as current *sinks*; that is, a current regulator biased with respect to the negative rail, often using one or more NPN transistors to *sink* load current. This is the terminology I will use in this article; i.e., a *current source* operates between a positive rail and the load or common, and a *current sink* operates between a negative rail and the load or common.

To add slightly to the confusion, there are single transistor devices that, because of their unique bias flexibility, can operate as either a current source or sink. An example would be the *common junction field effect transistor*, or JFET. So, in applying such devices, their explicit connection details will determine their exact function. More specifically, N-channel JFET devices such as the J202 and others exhibit this type of flexibility, and will be illustrated shortly.

WHAT TESTS?

While there are many tests potentially useful for audio characterization, this exercise concentrates on power-supply rejection versus frequency, which yields a picture of current regulator impedance versus frequency. These two performances go hand-in-hand. For best immunity to power rail noise components, a wide rejection bandwidth is desirable within the audio circuits. This may not be immediately apparent, because unregulated audio rails usually have predominant 120 or 100Hz ripple, from which it is relatively easy to provide immunity.

A salient point here is that the AC to DC rectification process is by definition a wideband noise generator, by chopping the AC mains waveform into high peak current pulses in the typically used capacitor input filter. A Fourier analysis of the noise components will show there are ample HF components associated with such supply rails, not just the 100/120Hz fundamentals.

Another subtle point is that the audio circuits themselves don't have infinite bandwidth. Thus, while they may have some degree of good supply rejection at lower audio frequencies, in the ultrasonic range this rejection deteriorates, introducing the potential for power noise components to *intermodulate* with the audio. Of course, for high quality reproduction, the possibility of any such intermod must be minimized, either by careful filtering or the development of circuits intrinsically immune to the nonlinearities that can produce the intermodulation.

TEST SETUP

The general setup for this test series is as per Figure 2a of Reference 1, available at **www.waltjung.org/PDFs/Regs_ for_High_Perf_ Audio_1.pdf**. The test is basically a highly sensitive crosstalk measurement done in the analog domain, measuring the output of a circuit as it is related to a 20Hz-200kHz swept sine wave excitation. This method was originally developed for the 1995 series of articles on audio regulators[1].

In this current series of tests, the "regulator" under test is either a current source or sink, which is connected as per **Fig. 1**. Here, the device or circuit under test is a two-terminal (in some cases, three) current source device (or circuit) connected between Vin and the load. The load is simply a 1Ω resistor, Rload1. Note that unlike Fig. 2a of Ref. 1, no output load capacitor is used for this test. The rail driver circuit supplying the +18V DC excitation with a superimposed 1V RMS AC swept frequency signal is shown in Fig. 6 of Ref. 1. It is represented here as the dashed box figure.

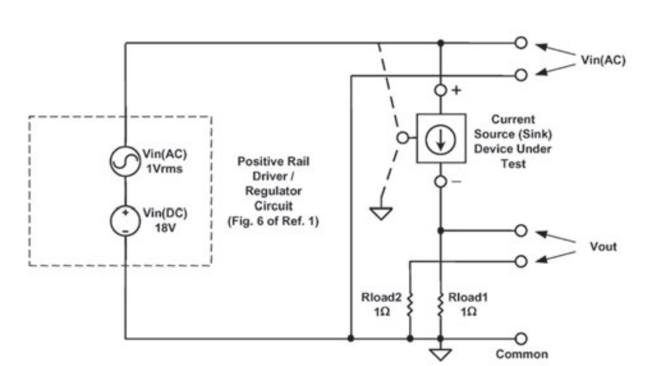


FIGURE 1: Current source/sink DC/AC test circuit.

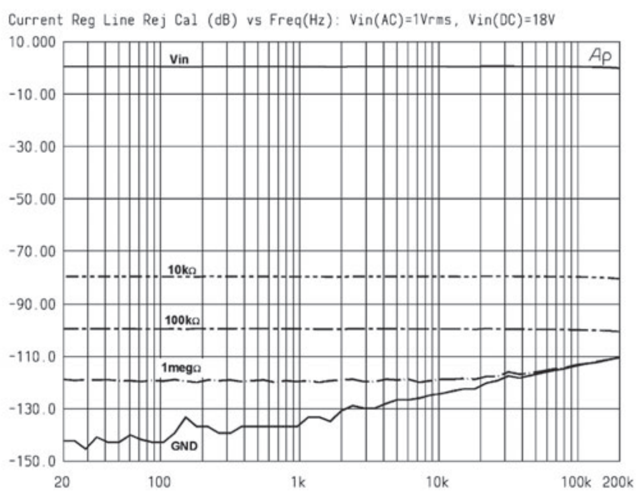


FIGURE 2: Multiple calibration runs with fixed 1% 10kΩ, 100kΩ, and 1MΩ resistors establish measurement validity. The dynamic range limits correspond to Vin and GND.

Calibration of this test setup is done by first calibrating the Audio Precision test set to the 1V RMS 0dB level, against the applied rail driver Vin(AC) signal. All subsequent measurements are then referenced to this 0dB level. The calibration is completed with a series of test runs, using fixed 1% calibration resistors in the Device Under Test (DUT) position. This step establishes corresponding reference Vout levels of 10kΩ, 100kΩ, and 1MΩ, as shown in the like-named plots of **Fig. 2**. On the dB scale, these correspond to levels of –80dB, –100dB, and –120dB, respectively.

In this figure there is also shown a much lower level trace, marked GND. This trace is the lower limit of the test setup dynamic range, which is the residual noise seen at Vout of **Fig. 1** with the test set active and no DUT connected. In essence, virtually all practical devices/circuits tested show appreciably higher levels at Vout, although some do indeed begin to approach the full dynamic range of more than 140dB.

As you can also note in **Fig. 2**, the plot for the highest fixed calibration impedance of 1MΩ falls about 20dB (or more) higher than the residual noise shown in the GND trace, at the lowest frequencies. At the higher frequencies, setup/system noise shows impedance lowering, corresponding to a dynamic range of ~110dB at 200kHz, which is roughly equivalent to 300kΩ.

THE MEASURED NOISE

The nature of this test is to measure, first of all, *synchronous noise*. This is because it is a modified crosstalk test, and operates by sweeping a measurement bandpass filter, looking at the spectrum appearing across Rload1. The measured noise, however, can be from either of two sources. The obvious one is due to the synchronous components related to Vin; i.e., the "crosstalk" noise components[1] (see "Hofer" box, p. 4).

But, another potential component could be due to any *self-generated* noise in the DUT. The test as configured here really has no means to distinguish one noise from the other—they are simply lumped together. It is true, however, that if and when a very low noise level is measured, both the synchronous as well as the self-generated noises must be low. And, in the many tests that follow, many circuits show very low noise—meaning that they have at or approaching levels of –140dB with respect to 1V RMS; in other words, on the order of 100nV RMS. A potential future investigation might examine self-generated noise more closely, with a higher load impedance and noise analysis software.

WHICH DO YOU PREFER: IMPEDANCE OR NOISE REJECTION?

You should understand that current regulator circuits may be specified in terms of either equivalent dynamic impedance; i.e., "100kΩ," or rejection with respect to some applied voltage reference level. Here, the three calibration impedances equate to rejections of 80dB (10kΩ), 100dB (100kΩ), and 120dB (1MΩ).

For impedances (Z) of more than 10kΩ (rejection of more than 80dB), you can use one of these approximations to convert between the two terminologies.

$$dB \sim 20 * \log (1/Z)$$

or

$$Z \sim 10^{(dB/20)}$$

In the test plots following, the current source or sink can be either a simple device such as a JFET, an IC such as a three-terminal regulator operated as a current source, or a more complex circuit comprised of transistors, resistors, and so on.

Referring to **Fig. 1** again, note that the measurement point of Rload1 is fixed with respect to the common point. For current *source* circuits, this is most appropriate, and the output current is measured directly and accurately. For some current *sink* circuits, a more appropriate current sample point would appear to be with Rload to the (+) lead of the DUT. This test setup doesn't provide for this, but nevertheless current sink type circuits can still be assessed. In the actual measurements that follow, this detail will become somewhat moot.

THE MEASUREMENTS

I measured a wide variety of current regulator circuits, all of which were built up on 8 pin header assemblies and plugged into the **Fig. 1** setup as a DUT. In the performance plots which follow, the Vin(AC) trace is shown at the top, and the GND trace at the bottom. The actual measurement data for a given DUT is contained in one (or more) Vout traces, which fall somewhere between the upper/lower dynamic range extremes. For cases of multiple Vout traces representing different conditions, each is labeled for clarity.

One Vbe Current Source

A "One Vbe" current source is shown in **Fig. 3A**, based on PNP transistors. In this and many circuits that follow, the transistors used are the high gain, TO-92 versions of general-purpose industry standards, either the 2907A series for PNPs, or 2222A series for NPNs. For general purpose work, these parts are preferable, since they represent a sweet spot of performance for these applications, that is excellent linearity for good rejection at lower frequencies, yet still

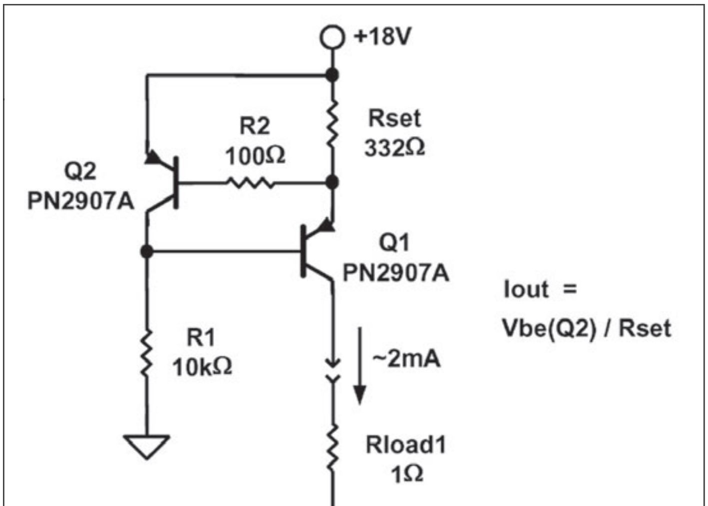


FIGURE 3A: One Vbe current source.

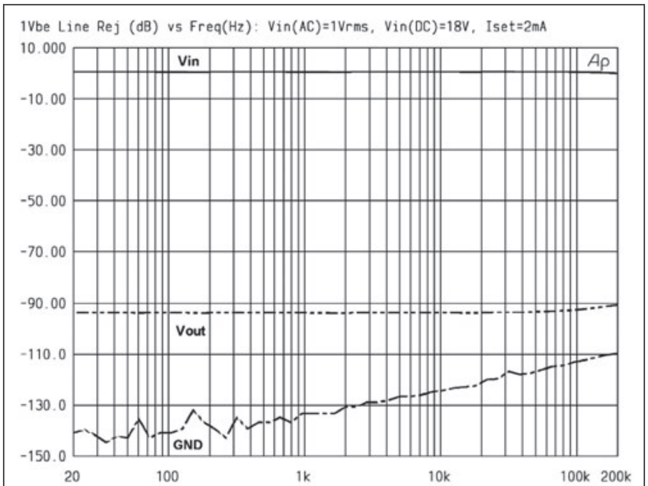


FIGURE 3B: The performance of the *Fig. 3A* "One Vbe" current source shows a rejection characteristic of about 93dB, corresponding to a 45kΩ impedance.

Bruce Hofer, Chaiman and CoFounder of Audio Precision Inc., offered these comments on the tests:

"I would like to note that System One is now an obsolete product having been replaced in the mid 90s with our System Two, which itself has gone through several cycles of evolution. The technique of displaying noise spectrally using a swept 1/3-octave filter is still valid, but some engineers today would probably prefer to look at noise using the FFT. I should also note that analyzer analog input noise has improved (dropped) somewhat since System One, but only slightly. Indeed, many of our competitors today have yet to equal the performance of our original System One! Thus I think your graphs are still quite relevant."

low-to-moderate capacitance, which allows the good performance to hold up well with increasing frequency, at great prices! They allow currents from low μA levels up to 20mA or more, at voltage levels of 40V (or more).

Of course, higher-voltage parts should be used when appropriate. While exotic and super-high-gain parts aren't necessary for very good performance from these circuits, low capacitance devices definitely are preferred (<10pF), a critical point if substituting. For truly excellent performance (at higher cost and reduced availability), you can use select "2S" series parts. Notable examples here are the Sanyo 2SA1016 PNP and 2SC2362 NPN (see www.semiconductor-sanyo.com/discrete/index.htm). These offer lower capacitance than the 2907/2222 families, and are useful up to 120V or more. They can work in the circuits shown, substituting for the PN2907A and PN2222A, respectively.

The familiar circuit of **Fig. 3A** is often used in audio circuits, perhaps due to the relative simplicity. It is configurable over a wide range of output current levels by adjusting the sensing resistor, Rset, which drops one Vbe (that of Q2) in operation. As shown, the output current is about 2mA.

The PN2907A types are useful up to medium voltages and several tens of mA. Q1 may require a heatsink for power dissipation of 0.5W or more. You can make a mirror-image current sink circuit with NPN transistors such as PN2222As for Q1-Q2, referring Rset to a negative supply. Note: This circuit can oscillate readily when using wideband transistors. The tendency to do so is suppressed by R2, which should be used with any form.

Performance of the **Fig. 3A** current source is shown in **Fig. 3B**, a plot of Vout for the cited test conditions. While the impedance offered by this circuit is rather independent of frequency, being flat to nearly 200kHz, it really isn't all that high. The rejection of ~93dB corresponds to an impedance of about 45kΩ.

While at first glance this might appear OK, the performance of this circuit is easily bettered by many others, both more simple and cheaper. For these reasons, plus the stability caveat, this circuit isn't recommended. Except as an example to avoid, perhaps!

Two Diode Current Source

An effective and still relatively simple current source is shown in **Fig. 4A**, again based on PNP transistors. With Q2 and Q3 connected as diodes, this is a two-diode-biased current source. It is often seen with two 1N914 or other diodes functioning just as Q2-Q3 do here. While it does use three transistors, it can still be inexpensive, because standard types such as these PN2907As are less expensive than metal film resistors. Output current is set by Rset and the Vbe of Q3, and is 2mA. As was true with the One Vbe current source, you can implement a current sink with the use of PN2222A NPN transistors.

Performance of the **Fig. 4A** current source is shown in **Fig. 4B**, where the impedance is again independent of frequency. Here the rejection of 100dB corresponds to an impedance of 100kΩ. This circuit is useful for moderate performance at low cost, at the expense of requiring five parts. Or, you could maximize efficiency by using the dual (or quad) packaged 2907A transistor types.

LED Current Sources

Replacing the two diodes of **Fig. 4A** with a single green LED forms the LED current source of **Fig. 5A**. This setup is slightly less complex and inexpensive, and provides good performance for the cost/complexity. Output current is set by the value of Rset, which has about 1.2V across it. The slightly higher voltage of a green versus red LED

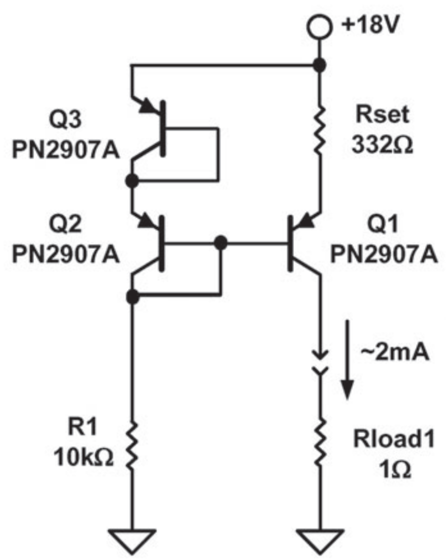


FIGURE 4A: The "Two Diode" current source. Q2-Q3 are diode-connected transistors, but can also be discrete diodes (1N914, and so on).

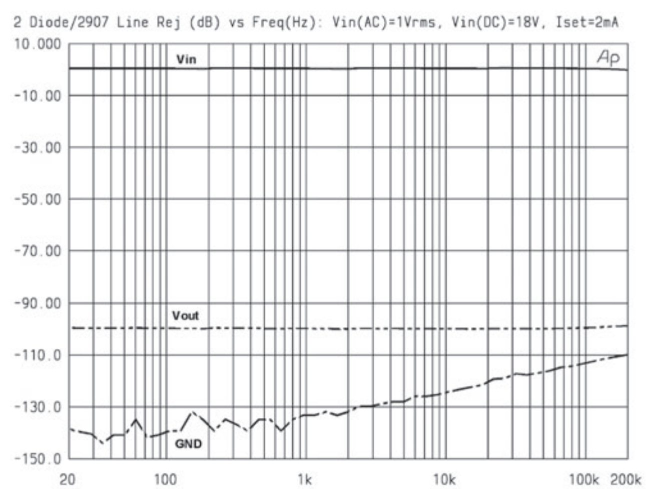


FIGURE 4B: The performance of the *Fig. 4A* Two-Diode current source shows a rejection characteristic of about 100dB, corresponding to a 100kΩ impedance.

provides the 1.2V, but you could also use a red LED. A current sink is also possible, using NPN transistors biased to a negative voltage, plus, of course, an appropriate polarity change for the LED.

Performance of this LED current source is shown in **Fig. 5B**, operating with an output current of 2mA. The rejection is about 105dB, corresponding to an impedance of 177kΩ. This circuit actually achieves better performance than the "two-diode" current source, but with fewer parts!

Reference Diode Current Source

If you replace the LED (with the relatively poor reference voltage) from **Fig. 5A** with a true voltage reference diode, a much higher quality current source is formed (**Fig. 6A**). Note that this form of the circuit has the same number of basic parts as the simple LED source, but is capable of much higher performance. This is due largely to the more stable voltage across the diode, which changes very little with current. An optional cascode connection for Q1 enhances performance considerably.

In this example an LM336Z-2.5V diode is used, resulting in about 1.8-1.9V across Rset. Thus a 1kΩ value for Rset supplies just under 2mA of output current. Note that the circuit is by no means limited to just such lower currents. As long as the power dissipation of Q1 is maintained low (or sufficient heatsinking used), currents up to 10mA or more are allowable from this basic circuit.

Figure 6B shows the performance of this simple current source in two modes, one basic, the other with Q1 operated with the optional cascode. In both cases the resulting performance is excellent. For the basic operation using a simply connected PN2907A for Q1 as shown at the left, the low frequency (LF) rejection approaches 130dB, which would be equivalent to 3MΩ. There is a slight rise in impedance at the upper frequencies, but all in all, the performance is exceptional for such a simple circuit.

When the optional cascode connection shown at the right is used, both LF and HF performance is enhanced. The cascode data, as noted, approaches the residual noise at all frequencies. It is enabled simply by using the optional connection for Q1/J1, which is, in turn, used as Q1 in the main circuit.

Note that this rather elegant connection is *self-biasing*, due to the manner in which the Vgs of J1 automatically provides a collector voltage for Q1. It will do so as long as the Idss of J1 is equal to or greater than

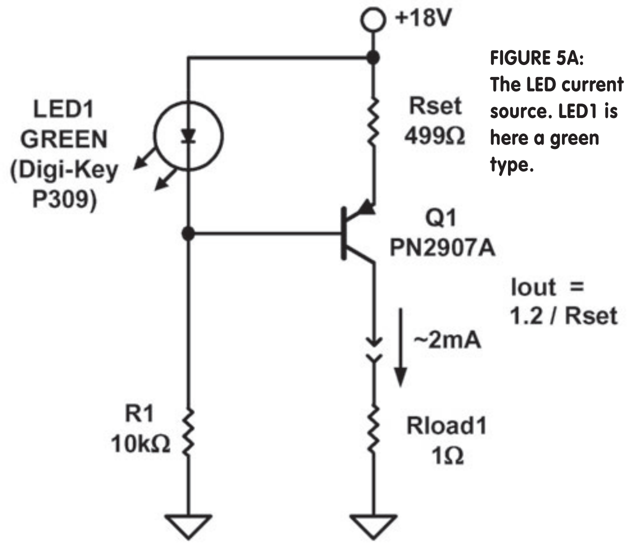


FIGURE 5A: The LED current source. LED1 is here a green type.

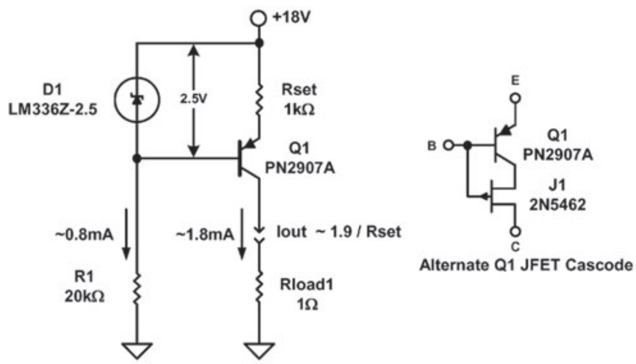


FIGURE 6A: 2.5V reference diode current source (basic, left) with alternate Q1 cascode (right).

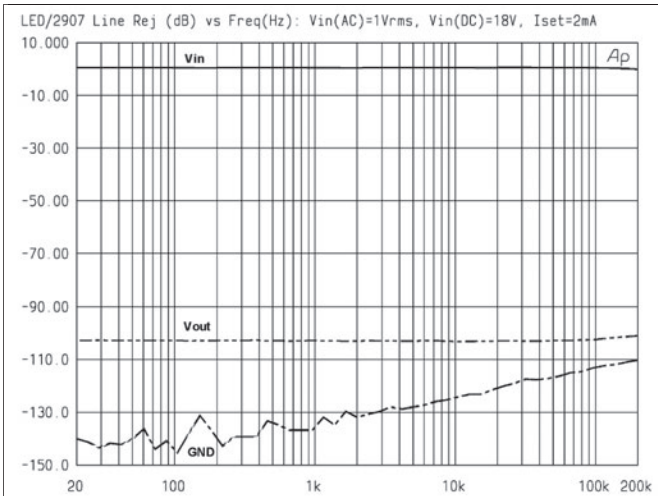


FIGURE 5B: The performance of the *Fig. 5A* LED based current source shows a rejection characteristic of 105dB, corresponding to a 177kΩ impedance.

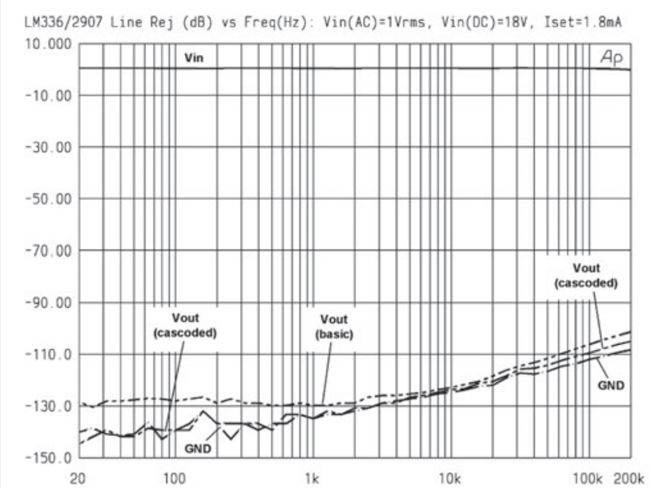


FIGURE 6B: The *Fig. 6A* reference diode current source performance for both basic and cascode operating modes. Cascoding greatly improves low frequency rejection.

the desired output current. For example, the 2N5462 specification for Idss is 4mA(min), which means that this cascode should only be used with lower currents, such as this 1.8mA case.

Alternately, for higher currents, either 2N5462s can be screened for a higher Idss, so that the tested Idss of J1 is always equal to or more than the desired Iout. Or, a basically higher Idss family of P-channel FETs can be used, such as the 2SJ74 V series (being careful to note that these are limited to 25V supplies). But, the 2N5460/5462 series is preferred, both from the standpoint of the low capacitance they offer, ≤10pF, plus their 40V voltage rating. The low noise 2SJ74 audio types have much higher capacitance than 10pF and don't perform as well as HF current sources (although they do excellent below 1kHz).

With a cascode connection such as this, you can expect a loss of output swing, due to the gate-source bias voltage of J1. Take care in testing at higher output swings to ensure that this is not a problem. The circuit of **Fig. 9A** following also discusses cascodes, at higher output currents.

Although the D1 reference diode used in **Fig. 6A** has low TC by itself, as it is applied here the net output current will still change with temperature, following a positive slope due to the Vbe of Q1. Another version of this circuit can also be built, using a 1.2V diode for D1. With this option, the output current will also have a positive slope of about 0.3%/ °C; i.e., the opposite of that of a conventional silicon diode. Although none of the current sources/sinks discussed thus far have low inherent TC, several examples to follow do in fact have both low TC and a predictable output current.

LM334 Current Sources and Sinks

The LM334 is a monolithic IC designed to be used as a current source (or sink), or, alternately, as a temperature transducer. It is shown in **Fig. 7A** (left), used as a basic 2mA current source, requiring only one additional part for functionality, Rset. The device features very simple operation and can be used up to about 5mA of current as shown. It is perhaps one of the more predictable types for output current among the circuits described thus far.

But, note that the LM334 output current is *not* constant with temperature; it does, in fact, vary linearly with a positive slope of about 0.33%/°K. The basic expression for output current is shown in the figure. Note that the very low sense voltage implies efficient utilization of power supply voltage. The part achieves operation at low thresholds, requiring only ~1V across the terminals to operate. Just as shown here, it is configured as a current source. Operation as a current sink is possible with the same number of parts, but with the V- terminal and Rset tied to a negative supply, with a load connected to V+.

Rejection versus frequency performance of the LM334 as both a basic and a cascode current source is shown in **Fig. 7B**. As will be appreciated, these impedance characteristics are exceptional, particularly at the lower frequencies where rejection is a few dB above the setup residual noise, even for the basic curve. This is indicative of an equivalent impedance close to 10MΩ, albeit with deterioration at the higher frequencies.

An improved version is available by adding a cascode-connected JFET, shown as the **Fig. 7A** option at the right. With this version, J1 is preferably a 2N5486 JFET, which is suitable for output currents up to 2mA. There are no other changes to the circuit. The beauty of this cascode connection is that it extends both low and HF impedance, and the resulting composite performance is barely above the residual noise level. The circuit can still be used either as the current source shown or as a current sink, with the load in the drain lead of the JFET.

However, it is important to note that selecting the JFET device for the cascode position really isn't trivial, but requires some careful thought. The 2N5486 series is quite useful because of the low capacitance and medium currents, *but it does have the disadvantage of only a 25V voltage rating*, lower than the LM334's 40V rating. Alternatively, the PN4393 family can operate to 40V, but it does have higher capacitance than the 2N5486 family of RF devices.

Other JFET parts can also work as J2. The basic requirement is that the desired output current be safely less than the minimum device Idss rating, and the JFET Vgs at the operating current is safely greater than the LM334 minimum voltage of 1.2V (~2V recommended). Some general considerations for the JFET selection are included on the LM334 datasheet[2], and in references 3 and 4. This process is also discussed in more detail with the JFET-based current sources to follow.

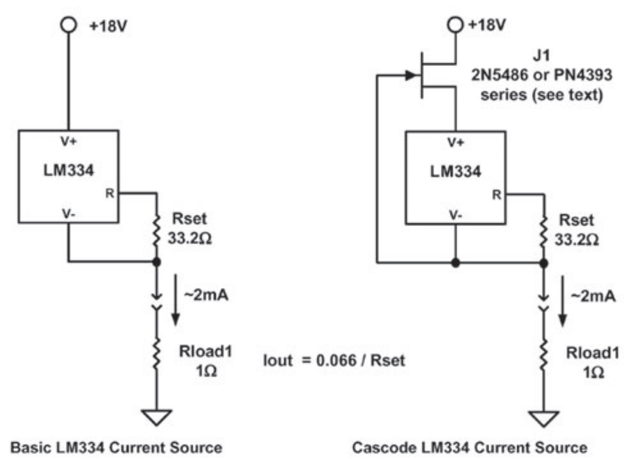


FIGURE 7A: LM334 current source (basic, left) with alternate cascode (right).

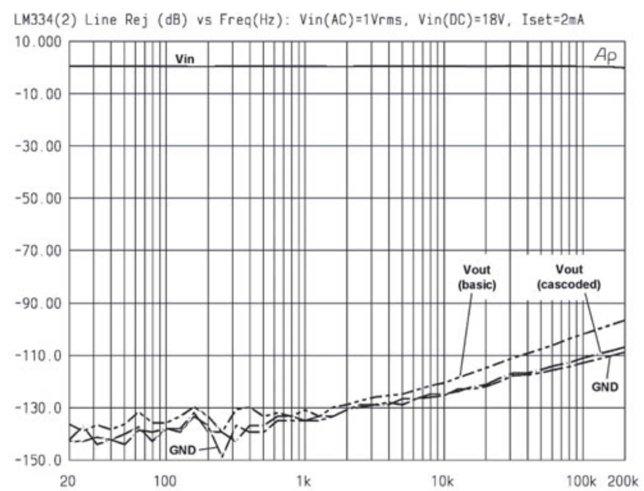


FIGURE 7B: The *Fig. 7A* LM334 current source performance for basic and cascode operating modes. Cascoding improves both low and high frequency rejection.

Some LM334 caveats: As typically operated, an LM334 produces noise components higher than that of a simple bipolar transistor at the same current. This is fundamental to the device design, so take this factor into account before application in low level circuits (see datasheet discussions). It will also have a higher output capacitance than many small signal transistors—about 15pF. Fortunately, this latter characteristic can be mitigated with the use of cascoding, providing that the cascode transistor used has low capacitance.

JFET-Based Current Sources and Sinks

It is fairly well known that many JFET devices make natural current limiters, and thus they can be used as either current sources or sinks. For an N-channel part (the most popular) all you need to do is short the gate and source terminals, apply positive bias to the drain terminal, and connect the gate/source to the load. Under these conditions the JFET will conduct a current equal to the device's Idss (drain current with gate/source common). Once the applied voltage is greater than a minimum voltage equal to Vgs(off), this current will then remain relatively constant with further voltage increases; i.e., the device is operating in a *current-limited* mode.

What is not likely to be as well known are the details appropriate to selecting a JFET part so that this supply voltage independence is maximized. For the testing described here, this implies the highest rejection characteristic. This is a function of both the specific JFET part itself, and how it is used.

A case in point is the simple JFET current source of **Fig. 8A**, using the J202 N-channel FET. While many different FETs can be used in this circuit, the J202 series is well suited to this application, because the rejection characteristics are optimum for the J201 and J202, which are 40V rated devices. They come from a family made with a *long gate* process, which minimizes the device output conductance, and thus maximizes the rejection. *An important note: References 3 and 4 cover this area quite well, and should be considered required reading for anyone building these types of circuits.*

Within all the various JFET process families, there are typically several classifications of devices, sorted as to Idss and Vgs(off) limits. The lower Vgs(off) parts in a given family will have the lowest output conductance, and thus the best rejection. For this family, this would be the J201, which has a max Vgs(off) of 1.5V. From Reference 3, for best rejection, the J1 Vdg > Vgs(off), preferably 2 * Vgs(off). Practically speaking, this means that such FET circuits like lots of voltage to achieve their best performance.

But, it isn't always possible to use such a low Vgs(off) part, as in this case I needed 1mA, which is well above the J201's minimum Idss of 0.2mA. So I used the J202, which, fortunately, still gave great results.

Although the most simple circuit of this type would use an R1 value of zero, I set up these tests with R1 = 100Ω to simplify selection of a device sample to conduct 1mA, the target output current, which occurs with 0.1V across R1. This device was then used in the rejection tests. It actually helps the circuit a bit to use some finite resistance for R1, because this resistance increases the net output impedance slightly. Consider it optional in your final circuit. Store-bought JFET current limiters simply short the gate-source terminals and sell the so-wired part as a two-terminal device (equivalent to the J1 part of the **Fig. 8A** circuit with R1 shorted).

Performance of the J202 as both a basic and cascode JFET current source is shown in **Fig. 8B**, and as you can note, even the basic circuit is excellent, considering the simplicity. The rejection is about 113dB, corresponding to roughly a 446kΩ impedance. While this can be considered very good for such a simple circuit, this is really due to the optimum conditions. There is first the optimum type of device (the J202), then there is also the relatively high bias voltage of 18V, well above the 2 * Vgs(off) rule of thumb. Circuits which bias J1 at lower potentials would be expected to perform more poorly, particularly when Vdg approaches Vgs(off).

While the J202 current source in basic mode is excellent for the simplicity, adding a cascode device makes the rejection characteristics approach the measurement limits. A cascode version of this 1mA current source is shown within the right option of **Fig. 8A**. These measurements used a 2N5486 for J2, and the cascode mode data of **Fig. 8B** is barely discernible from the residual noise.

But, there are more caveats to remember about this cascode circuit. The cascode device must be selected to provide a bias for J1 that is above J1's Vgs(off), preferably well above. For the sample devices used here J2 applied

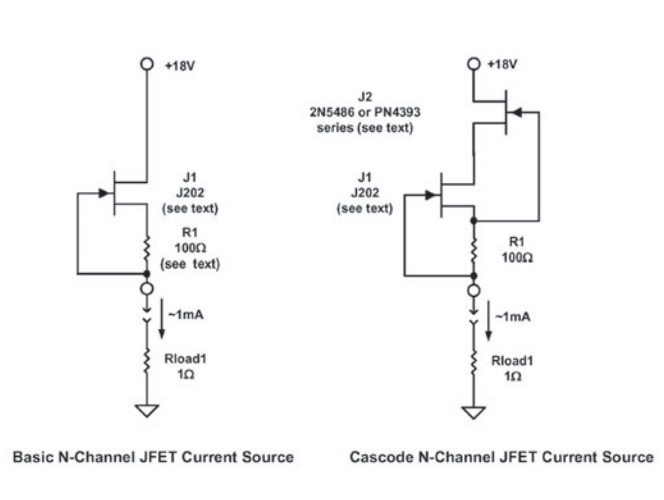


FIGURE 8A: N-channel JFET current source (basic, left) with alternate cascode (right).

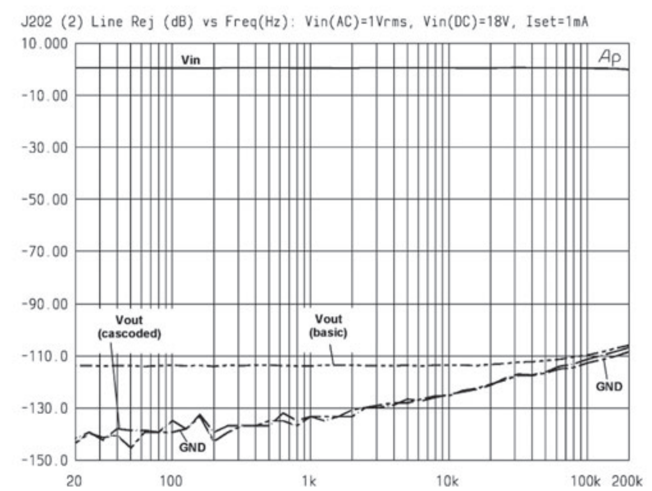


FIGURE 8B: The *Fig. 8A* N-channel JFET current source performance for basic and cascode J202 operation. Cascoding greatly improves low frequency rejection.

a 2.7V bias to J1, indicating that the sample J202 was a low Vgs(off) device. Furthermore, the 2 * Vgs(off) rule should also be applied to J2, and will be more stringent for that part, because it is by necessity a higher Vgs(off) part than is J1. The comments about deterioration of rejection with lower rail voltages apply even more so to this cascoded version, and may require supplies of 12V minimum, for example, for the very best performance.

So, in essence what you have here is a circuit that can work really well, but also exhibits some subtlety to extracting maximum performance. In fact, some J1/J2 preselection may be appropriate to set things up optimally. Fortunately, it appears that once the J1/J2 DC biasing conditions are properly met, the good AC performance falls in place. Watch the voltages on J1 and J2 and use higher voltage parts when necessary for the cascode. A caveat here applies to the 25V 2N5486, as noted.

Finally, I reiterate that both the basic and the cascoded versions of this current regulator can operate as either a source (as shown) or as a sink, with the JFET most negative terminal tied to the negative supply and the load in the positive leg. This is one intrinsic beauty of all JFET-based current regulators; that is, the ability to operate as either a source or a sink, without performance compromise. Note a somewhat subtle minor point here: you need only consider N-channel JFETs for such two-terminal current regulators; not only do they work (well), there are many more of them to choose from than the P-channel counterparts.

JFET Current Regulator Diode Based Current Sources and Sinks

Most of these discussions apply equally to JFET *current regulator diodes* (also called JFET current limiters), because they are JFETs internally wired as two-terminal parts. One series of these is the Vishay/Siliconix J500 family, consisting of individual parts with output current ratings from 0.24mA (J500) to 4.7mA (J511), all rated for 50V operation[5]. Of this series I had some J507s on hand, rated for a nominal 1.8mA operation, and some of these were tested.

Applying this type of current regulator is simplicity itself, as shown in the simple two-part basic test circuit of **Fig. 9A**, using a J507 as J1. Virtually all of the performance characteristics of this circuit are dependent upon the basic J1 part (and to some extent the ap-

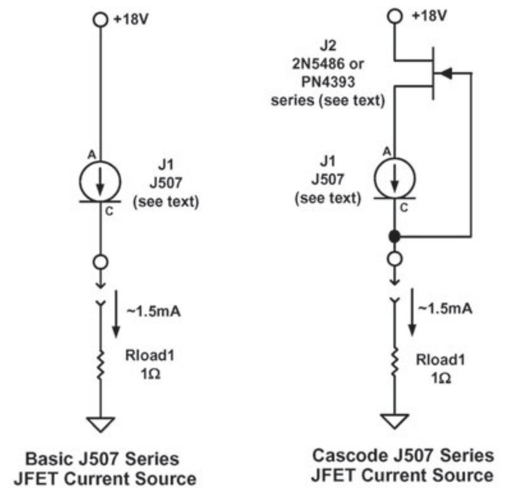


FIGURE 9A: J507 series JFET current source (basic, left) with alternate cascode (right).

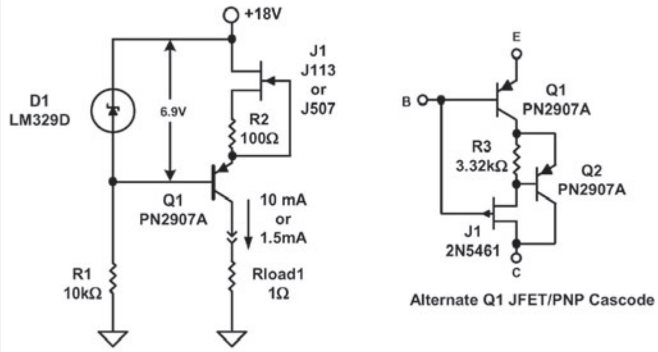


FIGURE 9C: A reference diode buffered JFET current source. Basic operation is shown at the left, with an alternate cascode connection for Q1 shown at the right.

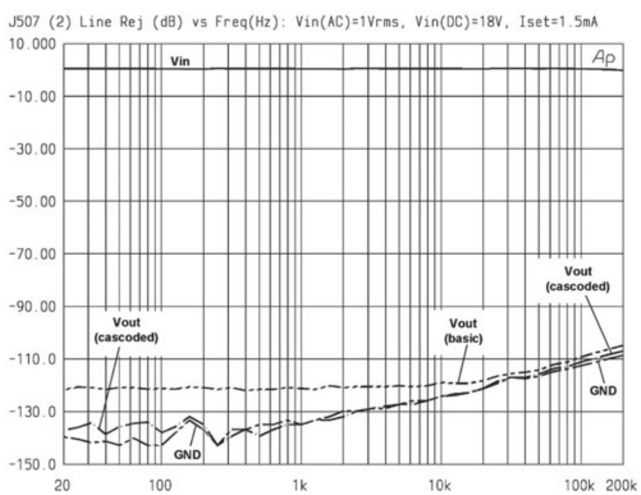


FIGURE 9B: The *Fig. 9A* J507 series current source performance for basic and cascode J507 operation. Cascoding greatly improves low frequency rejection.

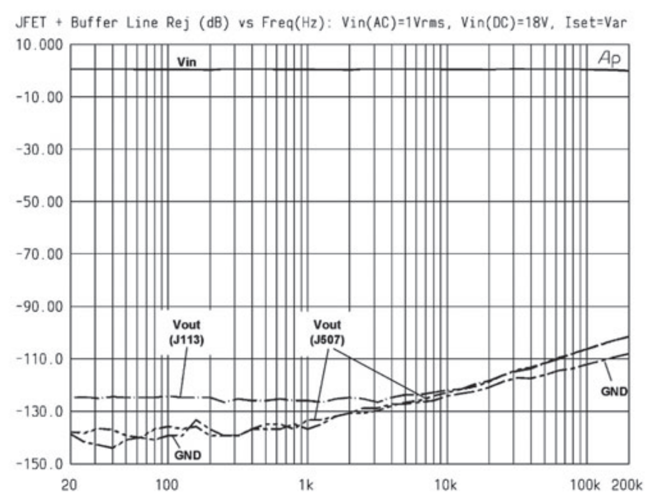


FIGURE 9D: The *Fig. 9C* buffered current source performance for basic 1.5 and 10mA operation. The J113 higher current decreases low frequency performance.

plied voltage). In the case of the J507 sample, an output current of ~1.5mA resulted.

Figure 9B shows the performance of this circuit for both basic and cascode modes. For the basic mode, the LF rejection is 120dB, equivalent to a 1MΩ impedance. Even at the higher frequencies the impedance is still excellent, rising only slightly above the noise level.

The two-terminal J507 is cascoded with a JFET as shown as the right option in **Fig. 9A**, a hookup very similar to the JFET cascode of **Fig. 8C**. For the J500 series, a minimum limiting voltage bias is given on the datasheet, which for the J507 is 2.5V. Thus any cascode circuit should provide a bias from the cascode part above this voltage to achieve best results.

The actual voltage for the parts tested was 2.6V, which was sufficient to allow the performance shown in the cascoded Vout plot. As you will note, this allows a LF rejection of ~140dB (10MΩ), and at higher frequencies performance just above the noise level.

Like the cascoded JFET circuit of **Fig. 8A**, you can apply this cascode to any part of the J500 series or to other similar JFET current regulators. You should choose the cascode device to supply the required minimum voltage across J1. Also take into account voltage limitations for J2, as in the case of the J2 device of **Fig. 8A**, right.

Reference Diode Buffered Current Source

The necessity for very careful attention with the JFET cascode biasing can be a real source of user frustration. Or, perhaps, a much higher voltage capability may also be necessary to get around a low JFET device rating, for example. A solution to both of these points is the reference diode buffered current source of **Fig. 9C**.

Here a 6.9V reference diode is used to bias Q1, a bipolar device, which allows operation up to the Q1 60V Vcb rating. The PN2907A is general purpose, but you can also substitute higher voltage parts, for example the 2SA1016. The 6.9V from D1 is reduced to about 6.3V across J1, which is sufficient to provide operation in the flat portion of the JFET device's output curve, where the rejection is highest. This is true at least for all devices of the J500 series, but some higher Vgs(off) individual JFETs could use even higher voltage bias (~10V).

Performance of this basic circuit is shown in **Fig. 9D** for two basic conditions: 1) a J507 operating at 1.5mA, and 2) a selected J113 JFET operating at 10mA. The J507 performance is generally very close to the noise level, except for a gradual departure at higher frequencies. The J113 is not quite as good, achieving a LF rejection of 125dB, which would be equivalent to 1.8MΩ. This degradation in performance is typical of many current sources when operated at higher currents. Fortunately, there is a solution for it, which is the application of a cascode device for Q1, as originally discussed with **Fig. 6A**.

But, in terms of basic operation, some notes on D1 selection are appropriate here. This diode need not be a high precision part, and even ordinary 1N5230 series (and other similar) zeners will work if chosen for a ~6V breakdown at the final operating current. Note that this can lead to some pre-qualification for proper operating voltage for any ordinary zener; that is, one specified for such higher test currents as 20mA.

It is for this reason that an IC reference diode is preferred here, to alleviate this voltage uncertainty and allow predictable operation at 1-2mA. If an IC diode is used for D1, it can be the loosest tolerance of the family without impacting performance. The LM336Z-5.0 can also be useful in this circuit.

Note that this circuit has similarities to **Fig. 6A**, but **Fig. 6A** depends upon the diode characteristics much more than this circuit. In this **Fig. 9C** circuit, the JFET (or other current source part) in the emitter of Q1 determines the output current, the stability, and so on.

For high currents, a cascode connection can be used for Q1, and will reap performance benefits similar to those noted for **Fig. 6A**, operated with the simple cascode. But the simple cascode using a JFET such as the 2N5462 will be limited to currents of just 4mA within this circuit. To allow a greater degree of freedom in the cascode device selection, you can use the alternate JFET/PNP cascode shown at the right in **Fig. 9C** for Q1. In this configuration, a lower current JFET part (the 2N5461) is used, and is operated at 200µA. In typical operation, this biases the source of J1 about 1V below the gate, sufficient to drive Q2 at currents of 10mA or more, without saturation of Q1. In essence a composite JFET is formed, with a much greater freedom of operating current, but, importantly, still retaining the self-biasing feature of Q1. The alternate cascode at the right replaces Q1 in the circuit at the left, with the C, B, and E terminals as noted.

The performance of this alternate cascode operating with the J113 at 10mA in the circuit of **Fig. 9C** is shown in **Fig. 9E**.

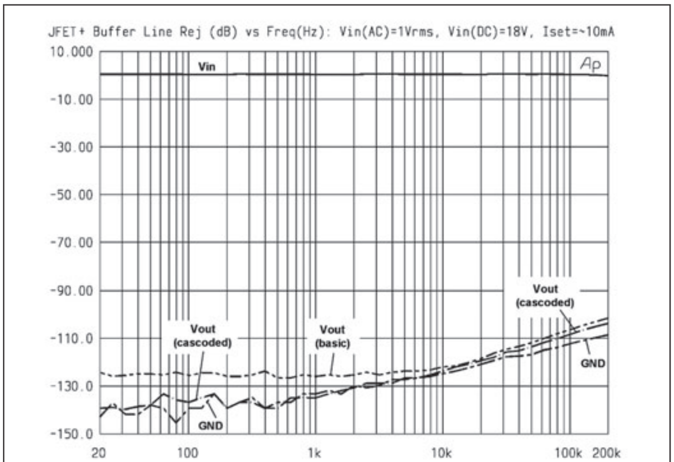


FIGURE 9E: The *Fig. 9C* buffered current source performance for basic and cascoded 10mA, J113 operation. Cascoding greatly increases performance.

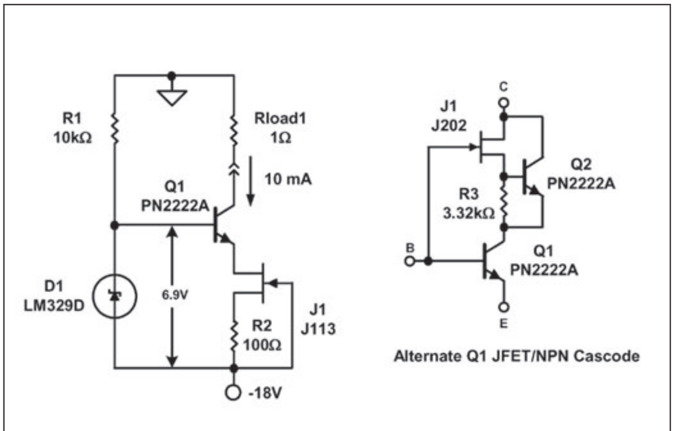


FIGURE 9F: A reference diode buffered JFET current sink. Basic operation is shown at the left, with an alternate cascode connection for Q1 shown at the right.

Now the LF rejection is comparable to the noise level, and the HF performance is also improved. The use of this cascode is recommended for any current above a few mA, or whenever the highest performance is required.

Reference Diode Buffered Current Sink

Comparably operated current regulators can be built to operate as current sinks, and have similar options to those of **Fig. 9C** for cascoding, and so on. Because it is potentially confusing to say simply "use mirror image connections and complementary devices," a full current sink schematic example is shown in **Fig. 9F**. The basic circuit at the left is an exact complement to **Fig. 9C** operated at 10mA, with the J113 setting the current. In the case of this current sink circuit, biasing is from a –18V supply, and the output drives load Rload1.

Cascoding Q1 of this current sink can be done if a JFET/NPN setup is used, as shown in the option at the right of **Fig. 9F**. This alternate JFET/NPN cascode can be used at currents of 5mA and up, without concerns of JFET device preselection. This optional circuit operates similar to the alternate JFET/PNP cascode of **Fig. 9C**, but here uses complementary devices. To employ this cascode, connect the noted C, B, and E terminals within the left basic circuit at the three Q1 nodes.

NEXT TIME. . .

Part 2 will continue these discussions, and will focus on higher current and higher voltage regulators with predictable, low TC output currents, and with very high rejection. It will conclude with some suggestions for applications and user modifications toward optimum use. *aX*

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5. "J500 Series Current Regulator Diodes," Vishay/Siliconix, July 2, 2001, www.vishay.com.

6. Selected and matched JFETs and JFET current regulator devices, as well as other audio components, are available from Borbely Audio. See www.borbelyaudio.com/audiophile_components.asp.