

# A Sources 101 Update

This article by the author of the *IC Op Amp Cookbook* and *Op Amp Applications Handbook* is an update and revisit of his "Sources 101" article, published in *audioXpress* in April and May 2007, as well as several follow-on letters, available online on the audioXpress website.



By  
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This article is a update and revisit of my "Sources 101" *audioXpress* article of April 2007<sup>[1]</sup> as well as several follow-on letters from September of that year.<sup>[2, 3]</sup> It deals with the basic test methodology and the relative validity for some specific current source types. For readers new to these discussions, a re-reading of the above articles will be necessary.

But first, some semantic terms need resolution. "The Amplified Negative Feedback Current Source" (Figure 4 of [4]) has been used as a name for the same basic circuit as what I call a "One Vbe current source," (i.e., Figure 3A of [1]). In these discussions, we continue with that original name, abbreviated as 1VbeCS.

## Two-Terminal and Three-Terminal Current Sources

These articles have dealt with *three-terminal* (3T) type current source circuits (see **Figure 1**) which have IN, COM, and OUT terminals. The

measurements are taken across a test load, Rload1 connected to OUT, with a DC bias plus an AC stimulus Vac applied to IN (see [1] again).

A *two-terminal* (2T) current source would not use a COM terminal, but would otherwise be the same (i.e., an N-channel JFET with G-S short, as in the J500 series).

As should be noted, this test setup can be reduced in simplest form to a three-element series circuit, as noted:

- (1) is the AC stimulus, Vac (with or without DC bias),
- (2) is the circuit under test or unknown impedance,
- (3) is the load, Rload1

Note also that a 1-2-3 element sequence arrangement vs. a 2-1-3 sequence will conduct the same current. The order of elements doesn't matter, since the current is the same in all elements.

At this point, Kirchoff's laws could be reviewed, should you so wish.

These 2T series circuit principles allow a measured voltage across (3) to deduce the relative Z of an unknown (2), with Vac being fixed. This may be more clear by referring back to the original **Figure 1** test circuit.<sup>[1]</sup> The basic functionality should also be evident from **Figure 3**, a 3T SPICE test circuit with a source of (1) Vac (superimposed on a 50V DC bias V1), (2) a test current source circuit U1, and (3) Rload1. A 2T circuit would be connected between IN and OUT, with no connection to COM.

For a 2T type current source being tested, the measured voltage Vout can be related inversely to impedance. That is, a reading of -140 dB re a Vac level of 1 V implies an impedance of 10 meg Ω, -120 dB ==> 1 meg Ω, etc. For example, from the data of **Figure 2**, the lowest frequencies realize measured levels around -140dB, equivalent to around 10 meg Ω. While this is a bit fuzzy due to the setup noise floor, the basic idea holds.

Note that this data is for an actual real 3T circuit, that of **Figure 1** (which is *not* 2T), and there is a dramatic difference between the case of C1 being present, or not. What is going on here, and why?

Before answering this, it should be acknowledged that the above measurement techniques have been challenged, specifically for such 1VbeCS types.<sup>[4]</sup> The stated objection is that a measured power supply rejection (PSRR) of X dB cannot be used to infer equivalent current source output impedance for a circuit such as **Figure 1**. The next few graphics will shed some very useful light on this point.

But first, it surely can be said the inverse relationship between relative decibel level and Z is specifically so, *for 2T unknown types*. Examples here are simple JFET current sources, or passive parts such as resistors and capacitors. In point of fact, the lab setup has been calibrated with resistances up to 1 gig Ω and capacitances down to 2 pF.

It has been consistently observed that 2T Rs and Cs measure just what they should. So this suggests that true 2T active current sources in general should also measure well, as shown previously.<sup>[4]</sup> This assumes proper active-circuit biasing, of course.

But, a potential discrepancy here lies within the nature of exactly how a 3T source behaves, versus a 2T type, for otherwise similar measurement conditions. As was noted, a 3T source has a COM pin, by definition. This basic fact has a tricky potential of making the current flow from IN to OUT depart from that of a 2T source. This can occur in some instances, *if the 3T COM pin current isn't appropriately accounted for within the design*.

As a result, 3T current source type impedance

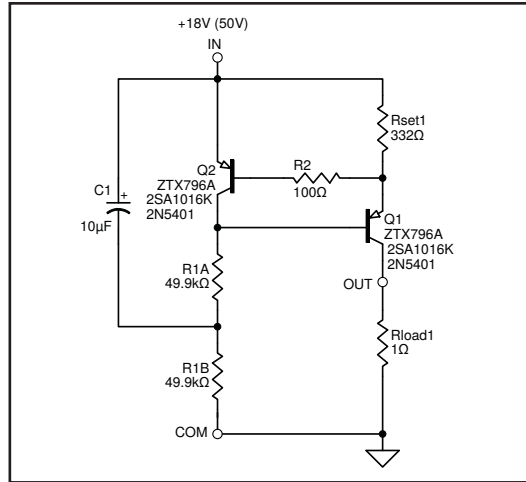


Figure 1: This one Vbe current source uses a bootstrapped capacitor C1. (Subcircuit Nodes IN, COM, OUT)

measurements, unlike 2T measurements, should not be casually related between relative decibel levels and an inversely related impedance. While a reading of "X dB" may be useful as a power supply rejection ratio (PSRR) figure-of-merit for a given circuit, that X dB won't necessarily be related to the circuit's true output impedance (i.e., the impedance as measured load-side).

This point was not covered originally, and I apologize for any confusion this may have caused. In fact, the working relationship between dB of rejection and a 3T source's true output impedance between is actually *conditional*. The uncertainty makes thing decidedly more complex. In fact, the

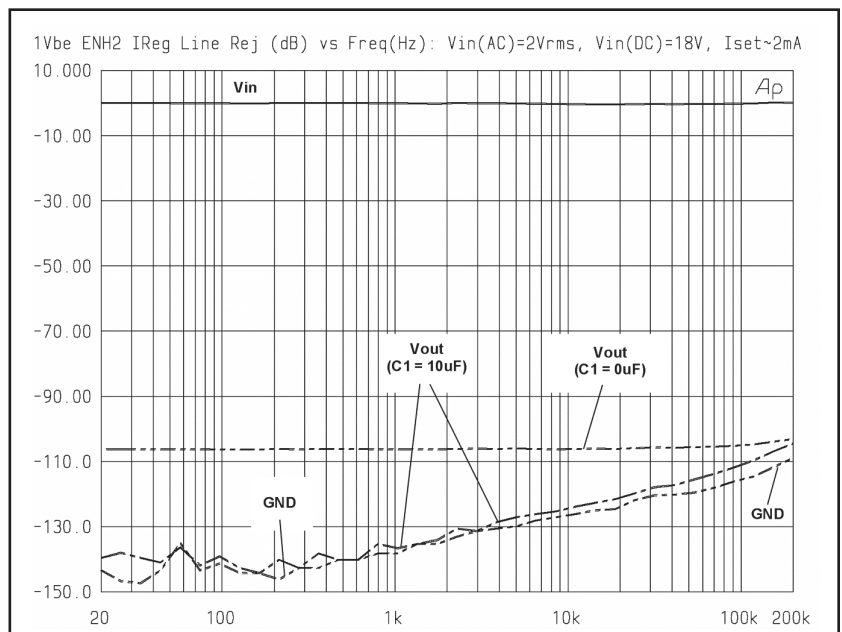
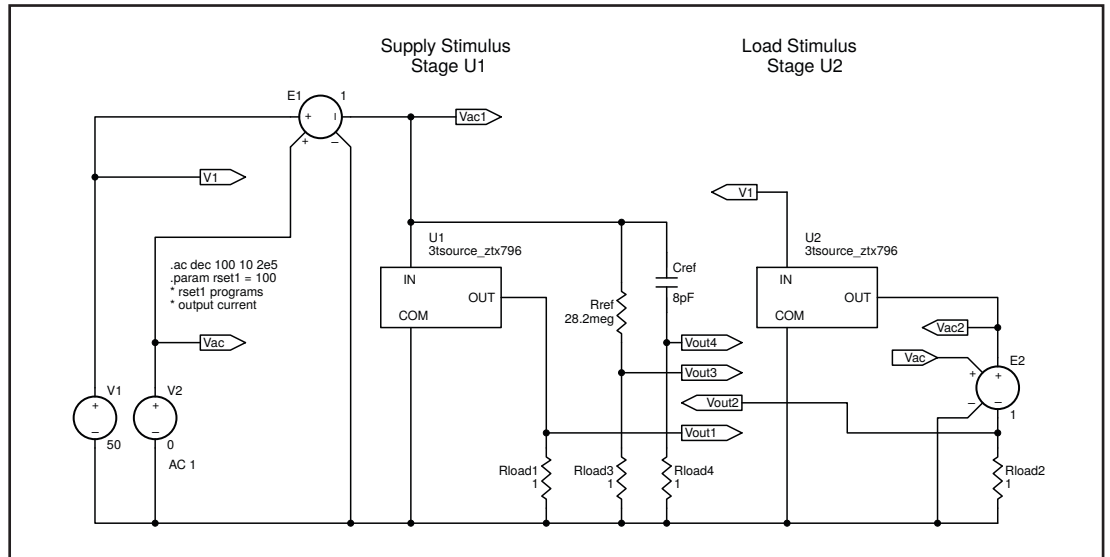


Figure 2: The lab performance of the Figure 1 circuit is greatly improved using C1. (The data was taken at 18 V/2 mA with 2SA1016Ks.)

Figure 3: A SPICE simulation circuit with 1 VAC stimulus is applied to dual Figure 1 current sources, supply side (U1) and load side (U2), with ZTX796A transistors in a one Vbe ~5 mA setup.



criticism of [4] is actually both right and wrong, with prevalence being dependent upon the exact context of the configuration.

Practically speaking, this means that one must consider the internals of a 3T current source circuit, to see exactly how it behaves. The 1VbeCS in question is a good example for explanation, as it shows both 3T and 2T behavior!

Thomas Bohley, Chris Paul and John Popelish commented on this original current source circuit and the substandard performance.<sup>[2]</sup> I agreed, basically, but also noted a key letter from Marc Whitney.<sup>[3]</sup> Whitney suggested looking into Doug Self's form of the 1VbeCS current source.<sup>[5]</sup> This connection uses a bootstrap capacitor, and split

resistor biasing. This step effectively immunizes the gain stage against supply variations (more on this later).

This scheme is shown in **Figure 1** (same as the circuit in [3]), in the form of a "Tee" circuit. C1 is a bootstrap coupling capacitor, and the total R1a plus R1b ≈ 100 kΩ value provides a Q2 current just like the (value-modified) original circuit (i.e., 160 μA) when operated on 18V. As the **Figure 2** performance plots indicate, this circuit really does have truly excellent line rejection, when using the 10 μF C1. The rejection at low frequencies is increased 35 dB or more, to a range of ≈ 140 dB, actually limited by the test setup. Above 100 kHz, more than 110 dB of rejection is available. This improved performance is had for one additional R and C, vis-à-vis the original version.

With the Tee circuit active, the 1VbeCS behaves as if the bias voltage across C1 is constant with varying input voltage. Take this point to a logical conclusion, and note that if one were to replace C1 with a ~25 V battery and remove R1b, the circuit actually becomes a 2T type! And, as such, it has similar properties for measurements. Understanding this chameleon-like property is a major key to using the 1VbeCS most effectively.

But, some caveats still do exist. The Tee circuit as applied to this or any of the other current source types (such as LED or diode biased) *will begin to lose effectiveness at low frequencies, or when C1 no longer exhibits low Z vis-à-vis the R1 resistances.*

For the example C1/R1 values, this degradation isn't readily apparent from the lab tests, but it could still be a potential problem for other conditions. Here, the goal was a low cap value, thus the lower -C/higher-R values. C1 can be a general purpose

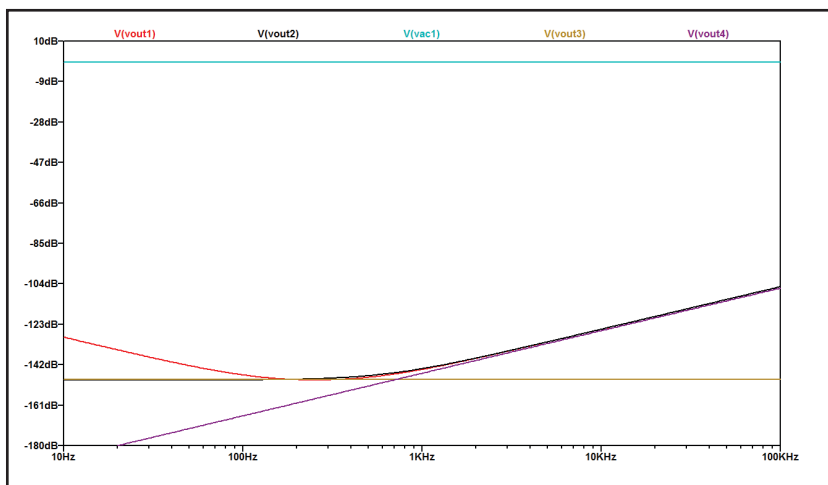


Figure 4: These are the SPICE simulation results for Figure 3. Supply Side Stimulus = Vout1, red < 200 Hz, black > 200 Hz Load Side Stimulus = Vout2, black > 200 Hz, brown < 200 Hz ~28 meg Ω Reference Resistance = Vout3, Rref = brown 8 pF Reference Capacitance = Vout4, Cref = violet

type, but it should be rated for a voltage about equal to the supply rail used. This will bias it conservatively (it sees only  $\approx V_s/2$ ). A very important point is that the scheme also applies to other current source types, as was noted in [3]:

*It is worth noting that this technique also works with other current sources of this type, among these are the "Two-diode" and "LED" variants discussed in Figure 4A and Figure 5A of [1]. The key step is to split bias resistor R1 into two equal parts, and apply the coupling cap to the midpoint.*

Some performance examples of this type of source are noted within **Figure 7** and **Figure 8**.

### The One Vbe Current Source: Revisited and Simulated for Both Supply-Side and Load-Side Impedance

Yogi Berra is remembered for numerous colloquialisms. Among them is: "You can observe a lot by watching."<sup>[6]</sup> For "observe" we take the Dictionary.com usage # 2: *To regard with attention, especially so as to see or learn something.* Of course, one definitely has to actively watch, in order to absorb/learn from a given experience.

A first case in point is the critical discussions of [4], which do not cite (and thus, do not observe) the specific points just reiterated (i.e., *suggesting use of the Tee circuit with three different current source types, from September of 2007*).<sup>[2, 3]</sup>

A second case in point is the simulated data of [4] as associated within **Figures 2, 3, and 4**, all of which focus on impedance *as measured at the load-side of the current source*. If we take the same circuit and also apply a stimulus *supply-side*, some very useful additional information is obtained. In fact, this information is critical to a fuller understanding.

**Figure 3** is an LTSpice test circuit which exercises the 1VbeCS of **Figure 1**, using the ZTX796A transistors with the Tee circuit values shown, at a  $\sim 5$  mA current, on a 50 V supply. The SPICE circuit uses U1 and U2 as a common subcircuit, noted in **Sidebar 2** (see References).

Note that for stage U1, the AC stimulus is applied *supply-side*, as Vac1, while for U2 it is applied *load-side* as Vac2 (as in [4]). Both simulation results are shown in **Figure 4**, and they are displayed similar to the lab test results for the same circuit as operated on 18 V (see **Figure 2**). As will be noted, the supply-side Z data (Vout1) and load-side Z data (Vout2) are overlaid above about 200 Hz. *In other words, they are essentially identical.* Below 200 Hz, the Tee circuit values begin to lose effectiveness, and the impedance seen from Vout1 begins to fall,

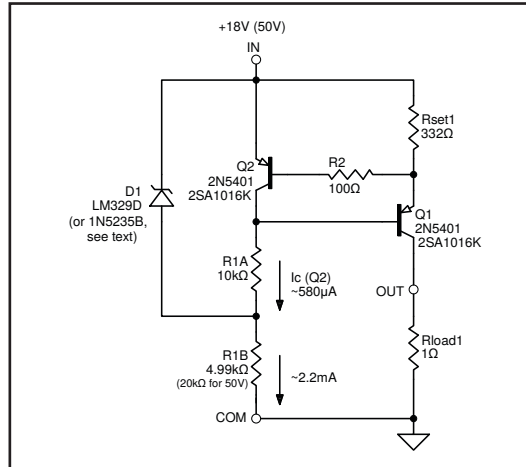


Figure 5: The Bohley one Vbe current source uses D1 Zener diode stabilization.

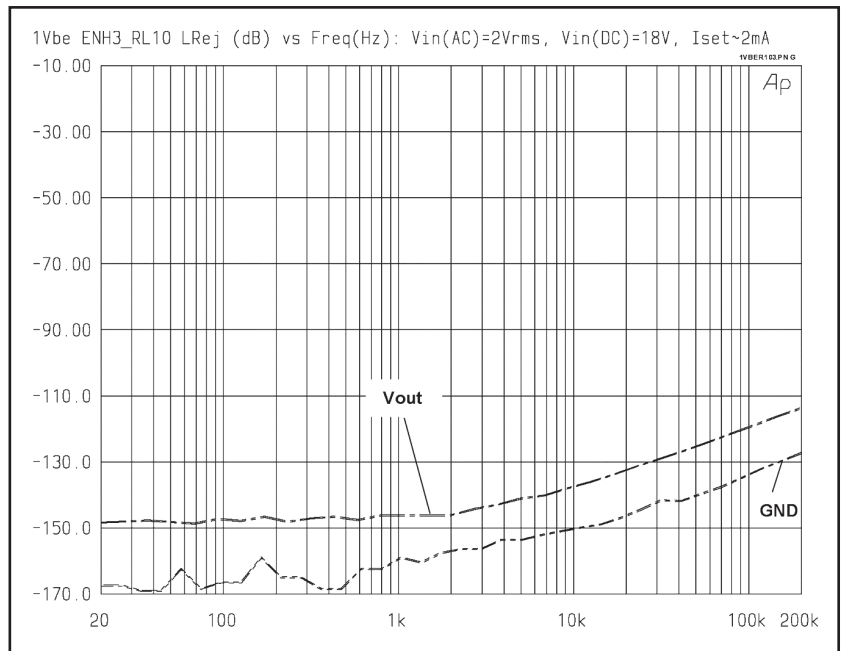


Figure 6: The lab performance of Figure 5 is essentially frequency independent below 2 kHz. The higher resolution setup allows better-performing circuits to be fully revealed. (The data was taken at 18 V/2 mA with 2SA1016ks.)

### About the Author

Walt Jung has been a writer on analog design topics since the late 1960s, specializing in op-amp and audio-related applications. His first *Electronic Design* article appeared in 1968, and many others followed, including his analog-oriented column "Walt's Tools and Tips." He authored many audio articles for Audio Amateur publications, starting in the 1970s and continuing with *audioXpress* in more recent years. In addition to writing numerous audio-oriented articles, Walt authored several IC application books, namely three editions of *IC Op Amp Cookbook*, as well as *Audio IC Op Amp Applications*. Most recently, he edited a book for Analog Devices Incorporated (ADI). Called *Op Amp Applications*, this book was a feature of the company's 2002 seminar tour. Walt has held senior level applications engineering positions with Linear Technology and ADI, and retired from ADI in 2002. He is a Life Fellow of the Audio Engineering Society and a Life Member of the Institute of Electrical and Electronics Engineers (IEEE).



represented by the rise of the curve. Below 200 Hz, the Vout2 curve flattens out to a -149 dB level, corresponding to around 28.2 meg  $\Omega$ . This is roughly comparable to the data of [4] (but not exactly, due to slight operating differences). An additional data point is the circuit's measured capacitance of  $\sim 8$  pF, as noted by the Cref curve, which is tangent to Vout2 at high frequencies.

So, what we see now is that with the incorporation of the supply-side stimulus data, we

actually now have a completely new performance dimension. In point of fact, this circuit behaves as if it is operating as a 2T type above  $\sim 200$  Hz, and as a 3T type below, as evident in the rising Vout1 (red) trace. For other C1/R1 values the frequency inflection point will move. A larger C1 will move the frequency where Vout1 and Vout2 depart downward in terms of frequency.

Nevertheless, it is remarkable just how closely these two Vout1 and Vout2 traces do track, above the frequency inflection point. It would be fair to say that there is little or no practical difference between supply-side and load-side stimulus, over this range. Then it follows that either method of stimulus can be used to characterize impedance for this type of circuit (i.e., either supply-side or load-side).

What we can now learn from all of this is just what is behind the conditional nature of the circuit behavior with supply variations. With the Tee circuit active in this 1VbeCS, the performance is superior, without it, things are much worse. But to the point of the [4] criticism, as used within **Figure 1**, *the Tee circuit enables the measurement of both superior PSRR and high output impedance*. That is, the load-side measured Z is virtually indistinguishable from supply-side measured Z. This is because the use of Tee circuit makes this 1VbeCS behave as if it were a 2T source. The bottom line? *We've observed a lot here, just by watching!*

### Sidebar 1: Notes Applicable to the SPICE Tests Shown in Figure 3

Vac1 from supply-stimulus buffer E1 = AC stimulus voltage for supply-stimulus stage U1 = 1v

Vac2 from load-stimulus buffer E2 = AC stimulus voltage for load-stimulus stage U2 = 1 V

Vout1 = AC output error voltage for supply-stimulus stage U1, in decibels relative 1 V

Vout2 = AC output error voltage for load-stimulus stage U2, in decibels relative 1 V

Vout3 = AC output error voltage of example;  $\sim 28.2$  meg  $\Omega$  Rref (-149 dB relative 1 V ==>  $\sim 28.2$  meg  $\Omega$ ) Vout4 = AC output error voltage of example; 8 pF Cref (decibels relative to 1 V)

### Sidebar 2: 3TSource\_ztx796.sub

\* This subcircuit produces a 1Vbe current source hookup with ZTX796A xstrs.  
\*

\* Usage: Connect IN node to DC source, COM to ground, OUT to load.

\* In top spice directive, program Iout with Rset1, as ".param rset1 = 100"

\*

```
.subckt 3TSource_ZTX796 IN COM OUT
```

```
Q2 N008 N001 IN ZTX796A
```

```
Q1 OUT N008 N002 ZTX796A
```

```
R2 N002 N001 100
```

```
Rset1 IN N002 {rset1}
```

```
R1b N007 COM 49.9k
```

```
R1a N008 N007 49.9k
```

```
C1 IN N007 10µ V=63 Irms=135m Rser=1.6 Lser=0 mfg="Nichicon"  
pn="UPJ1J100" type="Al electrolytic"
```

```
.model NPN NPN
```

```
.model PNP PNP
```

```
.lib C:\Program Files (x86)\LTC\LTspiceIV\lib\cmp\standard.bjt
```

```
* insert Q1/Q2 model file here
```

```
* ZTX796A*ZETEX ZTX796A Spice Model v2.0 Last Revised 4/3/05
```

```
* available from http://www.diodes.com/search?type=0&value=ZTX796A
```

```
.ends
```

### The Bohley One Vbe Current Source

In some email exchanges since his original 2007 *audioXpress* letter, Thomas Bohley and I discussed enhanced forms of this useful circuit that would have the same effect of raising the dynamic impedance of the R1a resistor, but without the use of the C1 electrolytic. The desire here is to both minimize component size and count, and to increase long-term reliability (not a feature of electrolytic caps). We agreed that a LM329 IC (a synthesized buried Zener type) functionally substituted in place of C1 would be a viable choice. Such ICs have very low dynamic impedances ( $\leq 1\Omega$ ), well below that of standard Zeners at a similar current. This lends considerable value to the circuit here, as this impedance works against a relatively high value of R1b, thus tending to keep both terminals of D1 near the supply voltage for dynamic changes. It is this factor that enables the circuit to emulate a 2T circuit, even though it is a 3T type.

A LM329-based version is shown in the Bohley 1VbeCS, as depicted by **Figure 5**. Here R1a is selected for a Q2 current of about 570  $\mu$ A, and R1b for 2.2 mA, sufficient to keep D1 in its operating range at low voltages. R1a needn't change for other

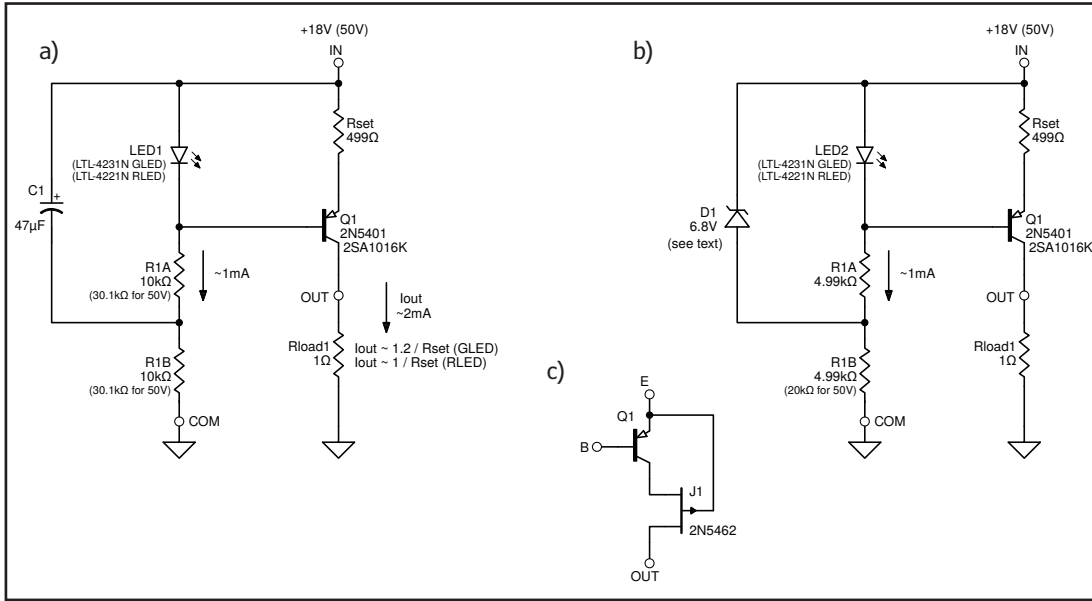


Figure 7: Two enhanced green or red LED-based current source(s)—with RC Tee circuit (a) or Bohley-style Zener Tee circuit (b). Note optional Csanky cascode (c) applies within either circuit.

supply voltages, but R1b must be changed, if the supply is substantially different. For a supply of 50 V, for example, R1b should be 20 kΩ.

This circuit was worthy of a test, to compare it to the 1VbeCS with the Tee circuit. And, it actually turned out better than expected, shown by the performance plots of **Figure 6**. These lab tests were done using 2SA1016K transistors, at 18 V and 2 mA (directly comparable to **Figure 1**), and D1 as an LM329. *Note the extended ~170 dB dynamic range, by virtue of an improved setup, allowing greater clarity for low levels.*<sup>[8]</sup>

The low-frequency rejection of this circuit is as good or better as the **Figure 1** circuit, as there is simply no low-frequency roll off below 2 kHz, as with the Tee circuit. And, the high-frequency performance is even better. A low-frequency rejection of ~150 dB would correspond to a Z of ~30 meg Ω. More significant is the equivalent capacitance, as evident of the 50 kHz rejection of ~125 dB, corresponding to under 2 pF...or about 4 times better than the ZTX796A test circuit performance of **Figure 4**.

This Bohley 1VbeCS also clearly outperforms the **Figure 1** Tee circuit based version, using the same component count. A very low cost version could also be realized, by using a standard Zener for D1 (such as the 6.8V 1N5235B). *So, once more we've learned a lot here, just by watching.*

I do hope others will recognize the merits of Tom Bohley's improved circuit, and find it as useful as I do. Indeed, a fitting tribute to his contribution.

### Some General Notes for These Enhancements

For these 1VbeCS enhancements, the choice of

transistors determines the ultimate performance, as well as the suited voltage ranges. Q1 should be a 2SA1016K or similar, for best performance. Q2 sees a much lower voltage, but, the lower capacitance 2SA1016K may be preferred here also. Performance isn't all about just voltage rating or low capacitance. In circuits where Early voltage<sup>[7]</sup> limitations come into play, the 2SA1016K PNP or 2SC2362K NPN can be more effective. A classic higher voltage part is the 2N5401, still available and recommended. In fact

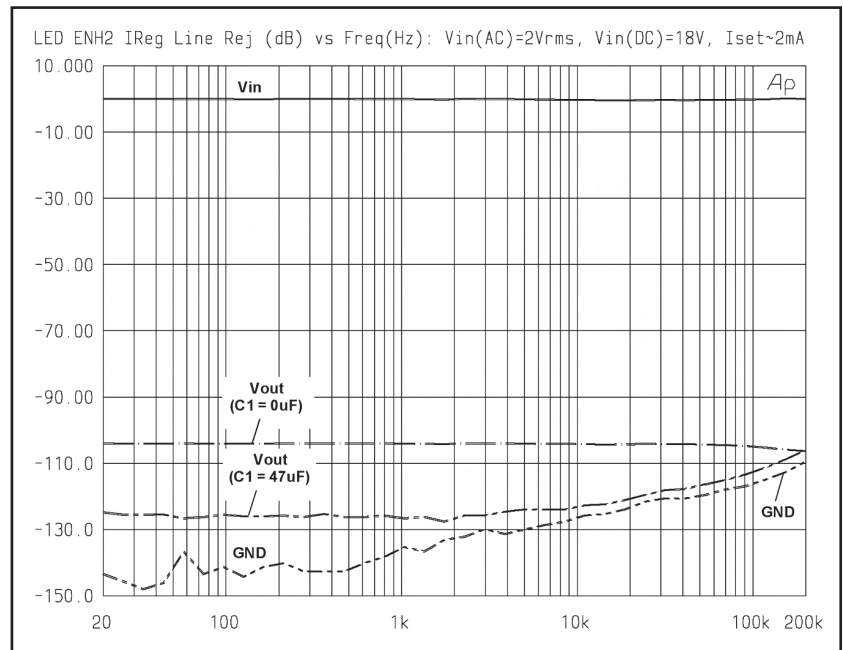


Figure 8: The performance of the circuit shown in Figure 7a enhanced LED current source shows an improved low-frequency and high frequency rejection characteristic when C1 is used. (The data was taken at 18 V/2 mA with green LED and 2SA1016ks, no cascode.)

several different PNP types were SPICE-tested in the **Figure 1** circuit, and all outperformed the relatively high capacitance ZTX796A (not recommended). A more recent device with notable specs for current source use is the PNP 2SA1579 (NPN complement of 2SC4102). These have a 120 V rating, and both low Cob and high gain. Right now these are not bench tested, but they do show high promise in SPICE.

While current *sources* have been shown in these PNP-based examples, analogously operated high performance current sinks are also possible. Just use NPN transistors with appropriate biasing for negative rails, reversing C1/D1 polarities as fit.

## Picking a Current Source Type

After the above discussions, a logical question is this: Which current source is best for me? Here

are some details that should help decide what fork to take, or, as Yogi said, “When you come to a fork in the road ... take it”.[6]

The 1VbeCS type of circuit offers excellent performance as noted above. Unlike the LED and diode-based types, it is not subject to errors or performance limiting due to transistor Early voltage, because of the corrective feedback loop. This is a major asset. On the con side of things, it has a built in temperature sensitivity, since the reference voltage is 1 Vbe. And, the transistors need to be chosen for performance points beyond just their voltage specs. Low capacitance is a big virtue here!

By contrast, the LED and diode-based sources are subject to limits due to the Early voltage of the transistor used. Thus, even when they are stabilized for line voltage variations, this will put a final upper limit on performance. Two variants of LED-based sources are shown in **Figure 7**, using the Tee circuit in **Figure 7a**, and a Zener stabilized version in **Figure 7b**. Note that either form could also be used with the two-diode versions, by substitution of two forward-biased diodes in place of LED1.

The main feature of **Figure 7a** and **Figure 7b** is that the use of a Red or Green LED1 device allows a low-TC to be achieved. This scheme was noted years ago by Pete Lefferts.[9] The forward voltage drift of the LED matches that of the transistor, assuming they both see similar dissipations. In these two circuits R1a (and or R1b) are chosen for a 1 mA in the LED. In the Zener version of **Figure 7b**, R1a sets the 1 mA LED current, and R1b the Zener current.

Performance of the **Figure 7a** Tee circuit version is shown in **Figure 8**. Here, as was true for **Figure 2**, the use of C1 is clearly beneficial. This example uses the 2SA1016k transistors, which are a good choice for minimizing Early voltage errors. As a result, performance is still quite good, just not nearly as good as the Bohley 1VbeCS of **Figure 5**.

As noted back in the original “Sources”[1], errors due to Early voltage limits can be minimized by the use of a cascode connection for Q1. Usually this would require extra diode(s) and an extra transistor for the cascode, further complicating things. A very simple and attractive alternative here is a bipolar/JFET cascode, some of which have the powerful advantage of being *self-biased*, requiring no additional parts beyond the cascode transistor.

A great example to be cited here is the Geza Csanky cascode, first described in 1963.[10] This patent shows a cascode using an NPN transistor combined with a *depletion mode* N-channel FET, in **Figure 4**. As noted, the enormous virtue of this

## Project Files

To download additional material and files, visit <http://audioxpress.com/page/audioXpress-Supplementary-Material.html>.

## References

- [1] W. Jung, “Sources 101: Audio Current Regulator Tests for High Performance, Part 1”, *audioXpress*, April 2007.
- [2] W. Jung, Response to correspondence from Thomas Bohley, Chris Paul, and John Popelish, *audioXpress Letters*, September 2007.
- [3] W. Jung, Response to correspondence from Marc Whitney, *audioXpress Letters*, September 2007, Figure 1 (schematic), Figure 2 (line rejection performance).
- [4] M. Kiwanuka, “The Amplified Negative Feedback Current Source and Voltage Source,” *Electronics World*, November 2016.
- [5] D. Self, *Audio Power Amplifier Design Handbook*, 4<sup>th</sup> Edition, Newnes, 2006. (A circuit with the current source in question is found as Figure 7.5. It also appears in later editions.)
- [6] Yogi Berra Museum Learning Center, <http://yogiberramuseum.org/just-for-fun/yogisms>.
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approach is that it is entirely self-biased, making it easy to implement given suitable parts.


The Csanky cascode can also be applied using a PNP bipolar and a depletion mode P-channel FET, as is noted in **Figure 7c**. For example, a low voltage PNP such as a 2N3906 could be used as Q1, with J1 a 2N5462. *Note that the FET must have an  $I_{dss}$  higher than the desired  $I_{out}$ , and the voltage limits of the FET must be observed.* Thus, the 40 V and 4 mA limits of the 2N5462 can restrict things. *Caution: Don't use Figure 7c on 50 V, unless you have a higher voltage FET!* But alas, higher voltage P-channel JFETs are quite scarce.

However, similar availability limits are *not true* for N-channel FETs, and in reality Csanky types of cascodes were shown in [1, 8]. In fact, the test setup changes of [8] mentioned earlier were necessary to resolve just how good a cascode of DN2540 MOSFETs can perform. So, this "all-weather" cascode would be a very useful fork to choose—the highest performance with just five parts! Not many current sources achieve combined

impedances of 100 meg  $\Omega$  and  $\sim 2$  pF. And, being a 2T circuit type, it is indeed an all-weather choice. A fork worth taking!

A useful bibliography of higher performance current source references is included in [11].

### Summary

Hopefully these discussions will enable users to select better performing current source circuits. 2T circuits are immune to the types of errors potentially seen with the 3T 1VbeCS described earlier and other circuit variants. If considering any 3T type of source, placing it within a SPICE simulation such as **Figure 3** should quickly show whether it can be useful. The files used in the simulations of **Figure 3** are included within the kit of [8]. 

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