LEDs as DIY Audio Voltage References

Part 2 of 2

A 1V Reference with Mirrors

Walt Jung

As noted within Part 1 of this article (available here), many modern LEDs have good utility as voltage references. Nominal forward voltage drops for popular single RED LEDs (RLEDs) are about 1.6 – 1.7V. The following circuit examples develop further the concepts covered in Part 1 and emphasize greater performance from RLED-based 1V reference circuits. In particular, they produce much lower noise than IC-based low voltage references, which is actually the major feature of the following circuits. They drop into familiar regulators of a 3 - 5V range.

To preface the actual reference circuit discussions later, it is useful to review the context of how it is applied. This is shown by ***Figure 2.0*** below, a simplified diagram for a low voltage, positive output regulator. Note carefully — this isn't a ready-to-build example! But, it does use key ***Super Regulator*** (***SR***) features. Control amplifier U1 is powered directly from the output, as is the 1Vref circuit. Q1 is driven by current source I1, and D1 provides level shift.

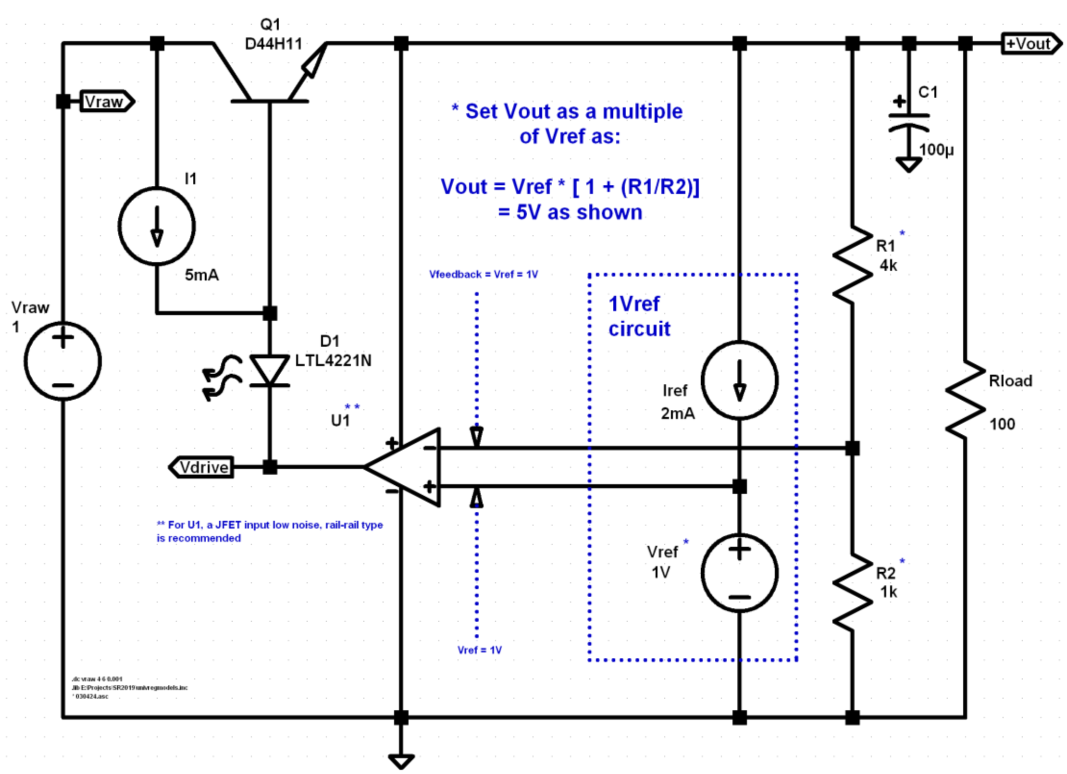
First, a Basic 5V Regulator using a 1V reference:

The Figure 2.0 circuit example contains a 1V reference in the dotted box, drawing 2mA from Vout. It also has a control op amp U1, and a power NPN Q1. The 5V or other Vout is scaled by the R1/R2 ratio.

With a Vref of 1V, both U1 inputs will always be very close to 1V. Within a mV or less. If U1 is a rail-rail output type, it easily drives the pass device, through low-noise level shifter D1.

So far, so good — but read on. A serious potential problem can exist if using low voltages, i.e., ~5V. While many op amps operate OK on low voltages, some FET input types can have limited common mode (CM) range, sometimes as much as 3V below the (+) rail. [1]

Figure 2.0: A 1V Reference as Applied Within a +5V Regulator.



If operating on 5V, check this out! Cases in point are the ADA4625-1 and OPA1641 JFET input devices, with restricted upper CM limits. On 5V they can't be used with CM inputs more than +1.5V! This disallows using them with references such as a 2.5V TL431. Nevertheless, do understand that they work fine with 1V inputs on 5V rails, as in ***Fig. 2.0***. All of this should be taken as simply a caveat towards potential frustration!

Now, For Some Smoke and Mirrors!

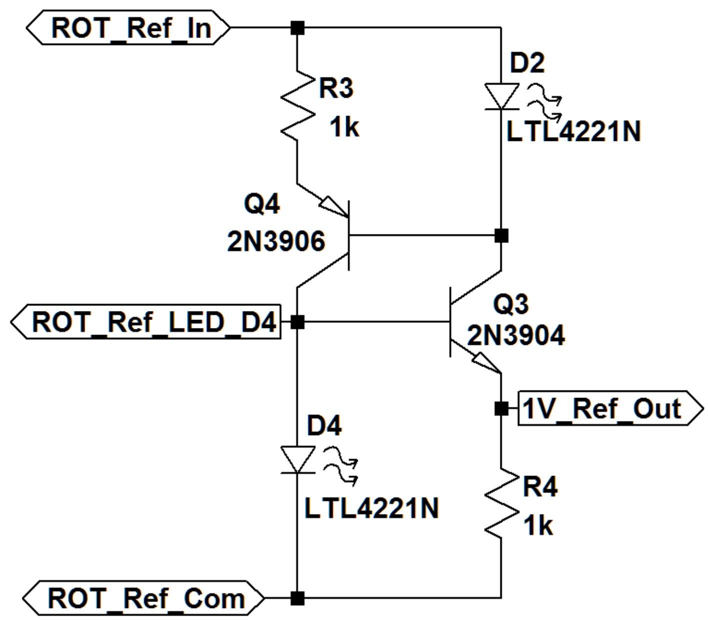
Looking back to the Peter Williams Ring-of-Two circuit of part 1 one can note that the ROT circuit actually consists of two current sources of opposing polarity, that is an upper source (Q4, D2 and R3) and a lower source (Q3, D4 and R4). These are inter-connected forming the ROT circuit. That form of the Peter Williams ROT was originated by Pete Lefferts using LEDs, as noted in Part 1. The basic Williams/Lefferts ROT circuit is repeated below as a ***Sidebar***.

As noted in previous discussions, the output node at the bottom,* ROT_Ref_Com*, passes two currents. These are set by the collector currents of Q3 and Q4. Within this ROT topology, the two currents aren't necessarily the same, but this is convenient.

This setup can be used as shown as a 1V reference, and is pretty good just as is. But it can also be made much better in terms of performance, with lower dropout, and better stability. Low voltage LEDs such as IR types show a Vf of ~1.1V at 1mA, so the circuit re-scaled for an IRLED for D2 and an appropriate R3, will then work for inputs of around 2V and up. To keep a 1V output, an RLED would still be used for D4, and Q3 a 2N3904. The IRLED used for D2 allows for lower dropout. With R3 = 500Ω, R4 = 1kΩ, the resistors are scaled for 1mA.

But, a subtle bit of magic comes about, when a Widlar-type current mirror [1] is used in place of D2 and Q4. In fact, if the Q3 current drives such a mirror, it reflects an output current, which is returned to drive diode D4 at the bottom. Scaling the mirror in a 1/1 ratio means that whatever current Q3 carries is mirrored back and drives D4 to the very same level.

Sidebar: A Williams/Lefferts ROT 1V Reference Using LEDs



Voila — therein lies the smoke and mirrors!

Note that with a 1/1 current mirror setup just described, *the input/output currents are always balanced.* Meaning this key feature: in the bottom portion NPN Q3 and LED D4 conduct the same current, greatly aiding stability, and making setup easier. Versus the Williams/Lefferts ROT shown, a Widlar mirror is implemented simply by making D2 and Q4 matched same type PNPs (with D2 a 2N3906 wired as a diode, and R3 = 0).

Skeptics might say, well, just how does it start? Doesn't the net positive feedback path make it unstable? Well, first note carefully that an LED with very low Vf looks much like an open circuit, and very much *unlike* the typical tens-of-ohms when conducting normally (Part1, again). So, for low input voltages, D4 is effectively open circuit, and small leakage current through the mirror above will tend to turn on Q3. The mirrored Q3 collector current then comes back around, driving D4. A regenerative process ups the loop current, and D4 turns on fully, then becoming a low impedance, whereupon the entire circuit is stable. [2] In the end, it regulates its own two currents, summed at the output node joining D4 - R4, or **ROT_Ref_Com**. Plus of course, there is the desired 1V reference output, **1V_Ref_Out**.

[1] R. J. Widlar, "Some Circuit Design Techniques for Linear Integrated Circuits," *IEEE Transactions on Circuit Theory*, Vol. CT-12, No. 4, December 1965, pp. 586 – 590 (see Fig. 1a). See also R. J. Widlar, "A Unique Circuit Design for a High Performance Operational Amplifier Especially Suited to Monolithic Construction," **Proceedings of the NEC**, Vol. XXI, October 1965, pp.85-89 (*The uA709 IC op amp*).

A 1V Reference with Mirror(s) — Basic Form:

Now to the right is a current-mirror-based LED reference that is one both more complete and more precise. In the simple two transistor mirror Widlar reference above, current can also be mirrored effectively, if the mirror uses high gain transistors, like the BC327-40. Or the SOT-23 counterpart, BC807-40.

However, the type shown here as Fig. 2.1 uses a Wilson mirror [2] which minimizes gain errors vis-à-vis a Widlar type mirror. This is further enhanced using high gain BC327-40 devices. The Wilson mirror has a higher input threshold, due to additive Vbes. This is mitigated somewhat by the BC327's Vbe, less than 600mV at 1mA.

This circuit then has roots in both the Pete Lefferts "LED-Based Current Source", as well as the Peter Williams "Ring-of-Two Reference". As shown here, the circuit is designed for a 1mA operating current in both D1 and Q1, the two reference core components.

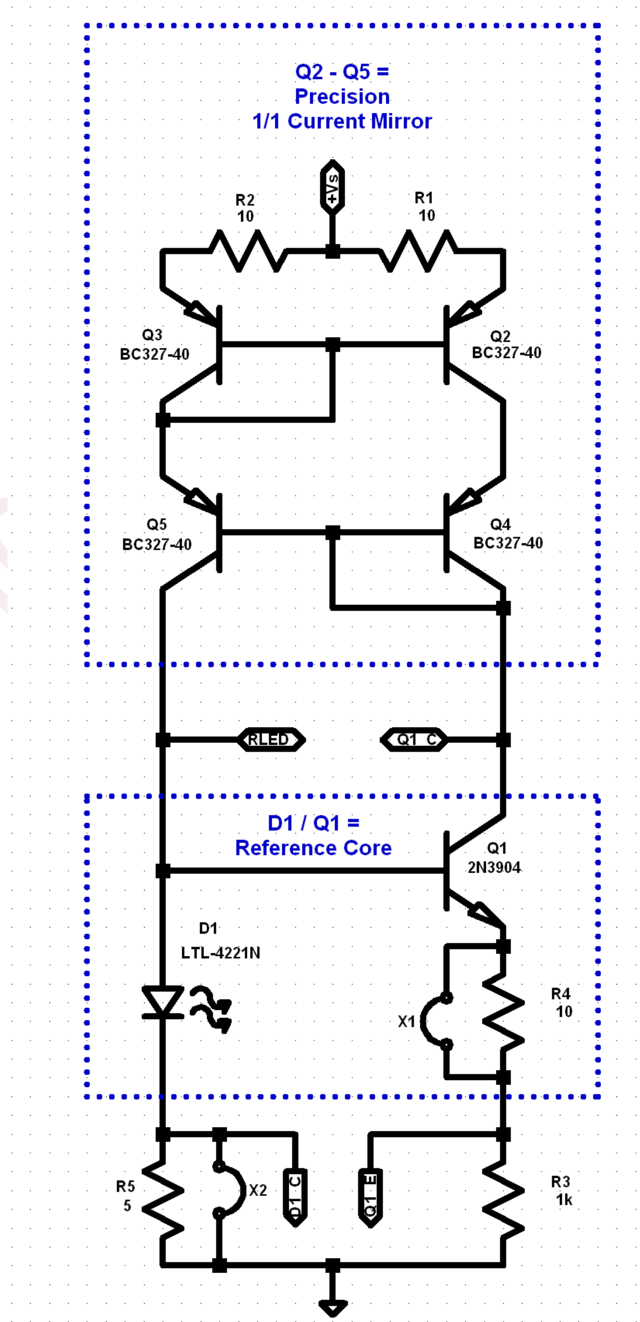
In the reference core, assuming a 1.670V Vf for RLED D1, plus a typical Vbe for Q1 of .670V, this produces (ideally) a 1V reference voltage output at output node Q1_E. Note that the operating principle is the same as the Williams ROT circuit. The notable difference is that a precision 1/1 mirror i.e., Q2 - Q5 of the upper box. This current mirror guarantees that whatever current leaves the Q1 collector is mirrored and returned to D1, automatically.

In practice some voltage trim may be necessary, either for the Vf of D1, and/or the Vbe of Q1. With jumpers XI and X2 removed, R4 and/or R5 allow for trim. But even without any trim, the D1/Q1 parts specified can produce an output within ~1% of an ideal 1.000 V.

Some early sample builds produced outputs about 10 mV higher than ideal, that is 1.010V. This might be good enough for casual use, and if simplicity is desired, you can build it just as shown. This entire circuit drops into the 1Vref box of Fig. 2.0, with 1V taken from the R3 top node.

But a potential caveat is *thermal stability*, which is optimum only when D1 and Q1 are coupled together and isolated from air movements. More on this point later.

Figure 2.1: A Basic 1V Reference Using a Precision Wilson Current Mirror.

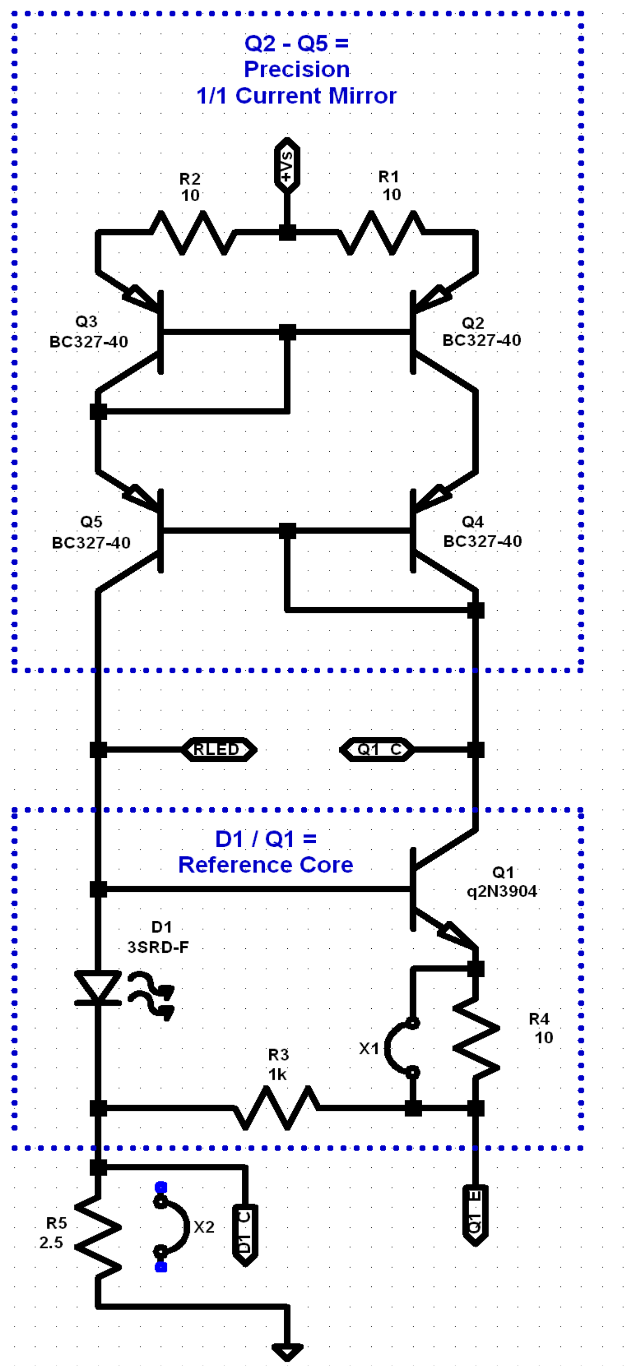


[2] George R. Wilson, "A Monolithic Junction FET–*n-p-n* Operational Amplifier", *IEEE Journal of Solid-State Circuits*, Vol. SC-3, No. 4, December 1968, pp. 341 – 348. See Figs. 6 and 7.

A Recommended 1V Reference with Mirror(s) Using *EzTrim*:

The flexibility of this basic 1V LED reference cell circuit is shown in the variation of ***Figure 2.2***. This is called the *EzTrim* form, for reasons soon obvious. Basically, this trim technique, with suitable D1 and Q1 parts, essentially can guarantee that virtually all samples will allow an easy trim. Thus, the name.

Figure 2.2: The 1V Reference with Wilson Current Mirrors, EzTrim Form.



In the** Fig. 2.1 **1V reference circuit just discussed, provision is made for trimming an output that is either too high, i.e., greater than 1V, or too low, less than 1V.

Too high case: ***Should the output across R3 be too high, R4 is activated by opening jumper X1. This reduces the output to 1V, assuming R4 is adjusted properly. There is always ~1mA flowing in R4, so a 10Ω R4 reduces output by 10mV.***

Too low case: ***Should the output across R3 be too low, R5 is activated by opening jumper X2. This raises the output to 1V, when R5 is adjusted properly. There is 2mA (total) flowing in D1 and R3, so an R5 5Ω trim value raises output by 10mV.***

Of course, the parts used for D1 and Q1 should be preselected so that a minimum of trim is necessary. In other words, when the Vbe of Q1 is subtracted from the D1 Vf, it should be very close to 1V. But trim may be necessary to get it within 1mV.

A feature of** Fig. 2.2 EzTrim form **is that it allows for a much easier one-step trim. **This is assuming that the nominal output from Q1 is too low.** ***This setup takes advantage of the fact that a stable 1mA flows in both D1 and Q1, under normal conditions. Thus, if the current of both D1 and Q1 are returned through a common resistance R5, the output can be raised higher for trimming. Again, the R5 current is always 2mA, the sum of currents in D1 – Q1. So, a 2.5Ω R5 value raises output by 5mV.***

With a Bivar 3SRD-F RLED for D1 and a 2N3904 for Q1, the output was found to be about 5mV low before trim. A 2.5Ω R5 value then brought the output to an error of less than 1mV. So, this example was an** EzTrim**, for sure!

But, a caveat should be noted regarding Q1. This specific set of conditions assumes a part equal to the original National 2N3904, later Fairchild, and now On Semi. All of these parts work well, but other vendors may not. Pretest for suitable Vbe!

Choosing the Best 1Vref Setup and Trimming:

Note that either circuit ***Fig. 2.1*** or ***Fig. 2.2*** will work with DC sources between 3 and 5V. You don't need to do anything beyond the initial setup and trim, and your 1V reference should then be good-to-go. This is a *stand-alone 1Vref* fashion, which is recommended for a great combination of simplicity and performance. Next a few examples of the D1 - Q1 selection centered around the recommended ***EzTrim*** setup of ***Fig. 2.2*** are helpful.

> ***EzTrim*** *procedure: Pick a suitable RLED for D1, a suitable Q1, work out the values, and trim R5 as required.*

To get an ideal 1.000V from the ***Fig. 2.2*** circuit, here is the procedure for three sample RLEDs, **(1)** a Liteon LTL4261NR, **(2)** a Lumex SSL-LX3054SRC, and **(3)** a Broadcom HLMP-Q150. Two of these are 3mm leaded devices, the third is a flat-lead unit, useful like an SMD with pads. A 1mA current is assumed for all. For testing purposes, build the circuit as noted, using a 3 – 5V supply voltage. The D1 – Q1 voltages noted below are derived from bench tests, so if you use other parts, carefully check a few for 1mA voltage drop. You can have more confidence if you average a few samples.

For an explicit caveat, *don't assume that just any RLED will work*! As a stronger caveat, some of the *SMD* RLEDs tested for these circuits were dismal failures with high or inconsistent voltages, and generally aren't recommended.

(1) Calcs for LTL4261NR:

- Vf(D1) = 1.6495V for **LTL4261NR**
- Vbe(Q1) = 0.670V for **MMBT3904 or 2N3904**
- Calculate R3 value as: (1.6495-0.670)/0.001 = **979.5Ω** Note: you could set Ic(Q1) to an exact 1mA, with 1k||47k. But first try it with a default 1k to see how close it is. It any event, you will be able to trim errors of 20mV or less, easily.
- Note V(R5) as: [(1.6495-0.670)/0.001] = **0.018V**
- Initial untrimmed value for R5 = 0.018/0.002 = **10.25Ω** . So, use a starting value of 10Ω and check output. Trim as necessary, allowing ample time for thermal settling after any soldering. *Note that a typical trimmed R5 may use 2 – 3 Rs in parallel if you want errors of 1mV or less.*

(2) Calcs for SSL-LX3054SRC:

- Vf(D1) = 1.652V for **SSL-LX3054SRC**
- Vbe(Q1) = 0.670V for **MMBT3904 or 2N3904**
- R3 value: **982Ω**
- V(R5) = **0.018V**
- R5 = **9Ω** Note: This is essentially the same as for the LTL4261NR, since the starting Vfs are very close.

Trim as for the LTL4261NR, starting with a trial 10Ω value. *Note that if a different Q1 device is used, these calculations must be redone.* The Bivar 3SRD-F RLED of the ***Fig. 2.2*** circuit works similar to the examples above, but it is actually so close in Vf just-as-is that trimming might not be necessary.

In general, note again that ***EzTrim*** works best when the Vout is appreciably *lower* than 1.000V, by a few mV or so. Then the added drop across R5 brings Vout up, as may be required.

A final example with an SMD compatible part wraps up this section. The quasi-SMD Broadcom HLMP-Q150, has a consistent Vf of 1.639V, and matches up well against either a BC547C or BC847C part. An ***EzTrim*** procedure for it is below.

(3) Calcs for HLMP-Q150:

- Vf(D1) = 1.639V for **HLMP-Q150**
- Vbe(Q1) = 0.645V for either **BC547C** or **BC847C**
- R3 value: **994Ω**
- V(R5) = **0.006V**
- R5 = **3Ω**

Dependent upon the specific D1/Q1 samples, you may even get a lower V(R5) voltage, and trim may not be necessary.

Some suggestions for minimum pain in the trim process:

- Don't try to trim out large errors, i.e., ≥20mV from ideal. Better to reevaluate the choice of D1 and/or Q1. The goal is Vf(D1) – Vbe(Q1) is very close to 1.000 V. Not 1.030 V, or 0.970V. Of course, these voltages pertain to operation at 1mA, not higher or lower. See this endnote on Vbe testing. [3]
- You will likely find that multiple shunt values may be necessary for R5 (or R4), so plan for this.
- Don't be in a rush in arriving at final value(s) for the trim resistors, especially if soldering in place. Thermal shocks from soldering take time to settle, so allow for this, and make sure Vout is not changing.
- If Vout is unstable for measured value, do make sure that air currents aren't the source of the drifts. *The principle of V(f)-V(be) = 1 is dependent upon* both *V(f) and V(be) seeing similar temperatures.* A good fix towards stopping such problems is to do this: once in the ballpark for an R5 value, cover D1/Q1 with a loose piece of heat-shrink tubing. Just covering the pair of devices will then show a stability improvement if this is the problem. Once you verify this, apply heat to shrink the tubing in place, and re-check for stable output.
- Note that trim resistor R5 should be external to the other parts of the circuit, or thermally separated. This will assure the best end stability. If all has gone as it should, you should now see very stable readings, that is <1mV of error in short term variations. That's <0.1% of 1V! Of course, there are no guarantees of this, but a well-trimmed 1Vref circuit with the right parts can show less than ½ of this.

Should I go Stand-alone, or Do I Need a Prereg?:

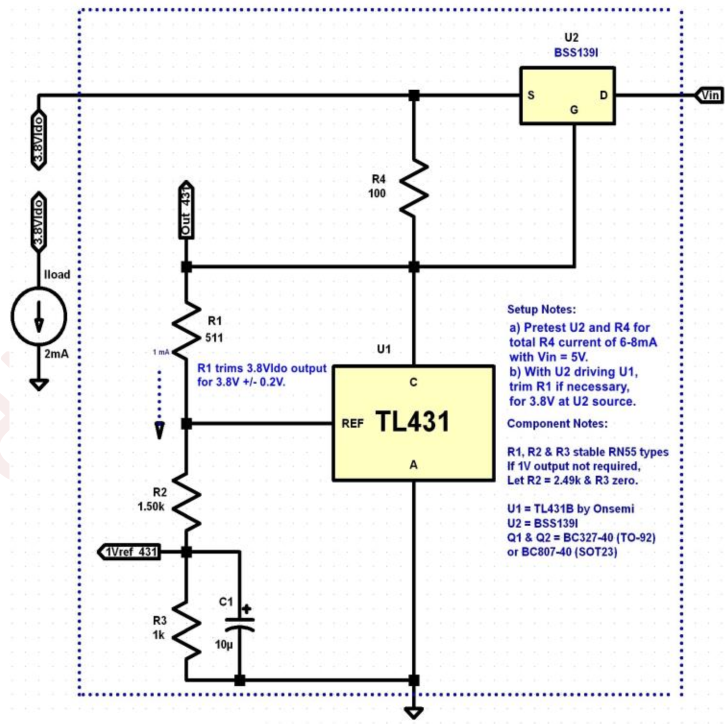
While either of the above 1V reference cell circuits can be used stand-alone, and you'll be all done. But they can also be used with a **Low DropOut (LDO)** preregulator, or prereg. This might be appropriate if the available source voltage is noisy or subject to drift. A scheme that operates this way is the LDO shown in ***Figure 2.3***. In general, this circuit is placed between the DC source Vin, and feeds the ultimate 1Vref (***Fig. 2.1*** or ***2.2***). This example 3V LDO prereg can be setup for outputs of either 3.1V or 3.7V, operating from DC levels of 3 – 5V. A 2mA 1Vref circuit Iload is assumed at the left, and this would be either ***Fig. 2.1*** or ***2.2.***

This Figure 2.3 LDO is based on the TL431, a 2.5V reference IC, U1. This is a basic TL431 hookup, with R1 used indirectly, to set up the output at the 3.8Vldo terminal. However, a key enhancement here is the current source feed, U2. The U2 Vgs appearing across R4 adds to the scaled output of U1, creating the LDO output **3.8Vldo.**

The U1 output **Out_431** ***is set by R1 and will always be higher than 2.5V. A fixed 1mA current is established by R2 - R3, and this total resistance shouldn't change. It can be simplified if a 1V output isn't needed, by making R2 2.49kΩ with R3 zero. The*** **Out_431** ***node then is set to 2.5V * [1 + R1/R2], or very close to 3V when R1 is 500Ω. This voltage is added to the Vgs of U2, summing to a final value close to 3.8V. The U2 source drives external load of Fig. 2.1 or 2.2.***

If used, the **1Vref_431** ***node is set by the R2/R3 ratio, providing a precise 1V scaling. In principle, this "free" reference output could also be used within a regulator like Fig 2.0, and this would offer very high DC precision with no need for any trims (within tolerances of course).***

Figure 2.3: A Simple ~3V LDO Useful Standalone, or With a Fig. 2.1 or 2.2 One Volt Reference



But alas, low noise isn't a virtue of most TL431 ICs. The On Semiconductor version is rated for a typical 50nV/Rt-Hz noise, which equates to 20nV/Rt-Hz referred to 1V. If used, the ***1Vref_431*** output as shown should be well bypassed by C1, an electrolytic in the range of 10 – 100µF.

Note that the ***Fig. 2.1*** or ***2.2*** RLED-based 1V references perform around an order of magnitude lower for noise level. That's their raison d'etre actually, but note it comes with a price. The tradeoff here is 1) DC precision with higher noise, within the simple ***Fig. 2.3***, vs. 2) much lower noise, but a basic trim necessity within the moderately complex circuits of either ***Fig. 2.1*** or ***2.2.***

For the highest overall LDO performance a BSS139I MOSFET is used at U2. Although the I suffix device of this series has a low Vgs, it still needs to be checked and matched up with an R4 value, to supply a 6-8mA current. This MOSFET best because of a low Vgs at the operating current, less than 1V. *A key to allowing a lower dropout is the fact that this setup does not place the Vgs of U2 in series, but instead it serves simply as a level shift.*

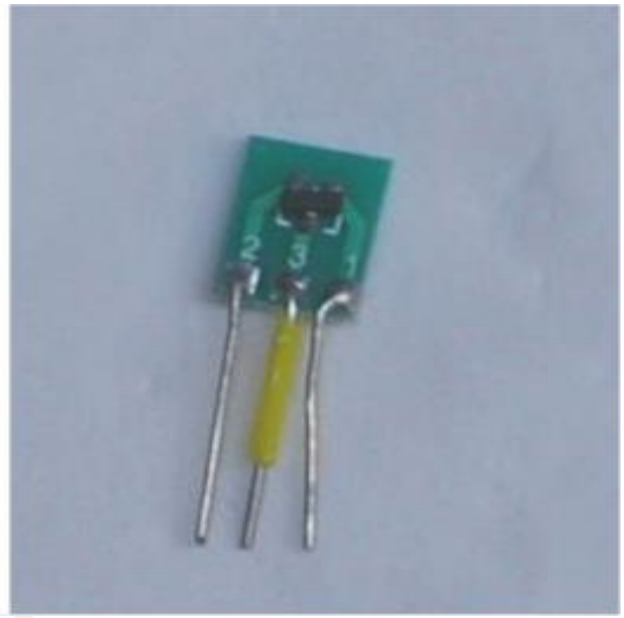
As a result, running on a 5V source, this means the ***Fig. 2.3*** LDO can output 3.8V, or even more. If being used with either ***Fig. 2.1*** or ***2.2***, the **3.8Vldo** voltage from the LDO equalizes dissipation between D1 and Q1, which helps overall stability. But this isn't super critical and voltages between 3 and 4V can also be used.

Pretesting a U2 BSS139I device for use in the ***Fig. 2.3*** LDO

The pretest of a U2 device and R4 value is simple. Plug them into a circuit, and check if a (nominal) 100Ω for R4 drops 0.6 to 0.8V, with a Vin of 5V. If so, the U2/R4 pair can be used in the LDO. If the value is off, use a higher or lower standard value that conducts ~7mA. The exact value isn't critical, as the shunt mode TL431 will absorb any excess current.

To aid in testing and handling of the tiny parts, an SOT-23 adapter can be used, as shown in ***Picture 1***, shown here with a BS139 soldered in place and leads added.

Picture 2.1 A 3 Pin SOT-23 Adapter is Useful for Testing BSS139I Devices



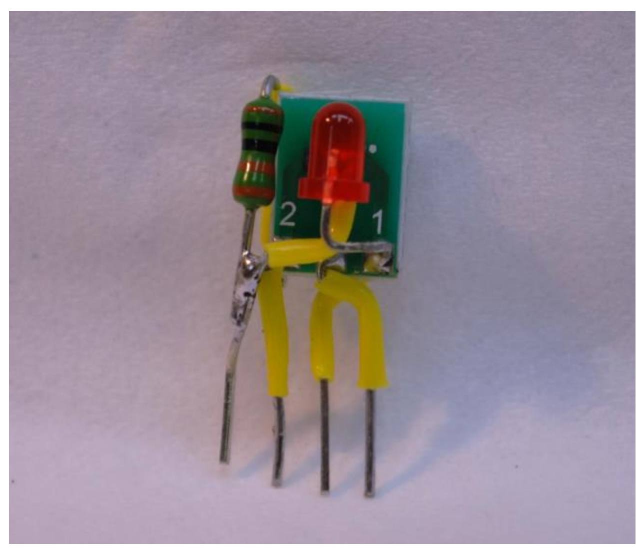
Setting up Final Output Voltage 3.8VLDO

Although a 3.8V output is suggested, this isn't necessary for all application of this LDO. Note that the net output from U2 is the TL431 voltage **Out_431**, plus the Vgs of U2. The latter was typically around 0.85V on the BS139I samples tested, but this can vary. In the end, some adjustment of R1 can be used to set , and this value can vary over a range 100 - 1kΩ, as may be necessary.

How to build it, in Steps:

Over the development period of these circuits, the most critical part comes with the physical mounting and surround of the core. For testing and qualification of RLED and NPN pairs, it was found that a 4-pin arrangement which plugs into a 4-pin, 0.1" spaced header help make things easy. Referring back to ***Fig. 2.3,*** this the would be the 1Vref core at the bottom. The current mirror part isn't physically as critical as is the core. ***Picture 2.2*** shows a sample with the Bivar D1 RLED soldered in place and covering the Q1 MMBT3904.

Picture 2.2 An RLED and R3 in* EzTrim *Form Mounted on a 3-pin Adapter



By making the 3 right-most terminals of this adapter pin out for the mounted SOT-23 Q1 as E-B-C, then with an added 4th lead for the cathode of the D1 RLED and R3, the core is complete. Note the common connection of R3 and D1, to the left.

Although this example has a 1kΩ R3 as mounted for an ***EzTrim***, it can also be deleted, so long as R3 is provided externally. For ease of plug-in operation use stiff leads with sleeving, to prevent shorts. Note: repurposed LED leads work well for this!

Proof of the pudding lies in the test for a 1.000V Vout. ***Picture 2.3*** shows a test readout which is around 6mV below perfect. The test reference core shown in ***Picture 2.2*** can be trimmed very close to zero error, using an R5 of around 3Ω (since 2mA x 3Ω = 6mV). In the end, how close one can get can easily boil down to what R values might be handy.

Here is where one might be tempted to use a stable film pot, to find a precise setting for R5, then measure it carefully, and substitute in a fixed value. A parallel combination of film types then can be used.

Picture 2.3 An Untrimmed Output from the Picture 2.2 Setup with R5 = 0

What is not shown next is the final form of the reference core just built and tested. Several such setups were tried using silicone sealant, which does in fact work. But this is messy, and also quite ugly. More clean and simple is to just use a length of shrink tubing which fits over the core. First recheck the Vout, and if OK, then apply heat to shrink the tubing and seal the D1 – Q1 core within. This gives a clean outer appearance, and the core can then be mounted to a PCB which carries the mirror parts. *But, don't miss a critical point required for orientation!* Leave one lead without the sleeving, and this becomes the R5 or common lead, as can be seen on the left side of ***Picture 2.2***.

Some Recommendations:

This project has been long and many-faceted. And, it is likely confusing in some senses, inasmuch as there are so many options to achieve a decent 1Vref based on RLEDs. Nevertheless, the most important thing to keep in mind is not to make it any more complicated than is necessary. Start with the basic ***EzTrim*** setup, and an RLED/NPN pair which will be easily obtained. For example, the LTL-4221N and a MMBT3904, which can likely result in an output within 1% of 1V, i.e., +/-10mV. Experience has shown this to be slightly high, so you can hedge your bet by including a 10 - 20Ω value for R4, with X1 open. Chances are good that this will result in very low error, and if so, you are done!

More complicated variants (LDOs etc.) should be left for later, should they be necessary at all. At this point, you are ready to put your ***EzTrim*** 1Vref circuit to work inside a real regulator. We wish you the best of luck with that, and some great listening at the conclusion.

Detailed how-to-build instructions are left as an exercise for the reader. Follow the above suggestions on thermal isolation of D1/Q1 from the environment, for best results.

Then, just enjoy your new regulator, and the clean music it can allow in your system. It will have a lower noise than with any low voltage IC reference now available!

Acknowledgments:

It is appropriate to note here the contributions of two types of individuals leading to this work. One is the legacy of Bob Widlar, George Wilson, Peter Williams, and Pete Lefferts. All of these people provided important work in the past, upon which this LED-based 1V reference is fundamentally based.

More recently, DIYAudio friends Radu Dicher and Igor Lucev participated over the past couple of years in research leading to what is shown above. Radu made valuable contributions in device voltage measurements and characterizations, plus key insights in physical layouts and useful parts such the neat SOT-23 adapter. Igor's outstanding find was/is the BSS139I MOSFET, a key part in an effective and low parts count LDO (above). He also built and tested varied series and shunt regulators, which present a huge challenge working at low voltages.

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[1] Igor Lucev first reported on the restrictive op amp CM issues vis-à-vis the (+) rail, when using certain low noise JFET op amps on 5V rails. This became a driving force for the low noise LED-based 1V reference which ultimately resulted. The much lower noise of the LED reference very nicely complements the JFET op amps.

[2] If there should be doubts about reliable startup, a simple 1meg resistor from Q1 collector to base within the reference core will provide a small startup current. But, it is worth noting that I have never seen any variation of this mirrored reference source fail to start, *if the reference diodes are operated without shunt resistance(s), i.e., as shown here in Figs 2.1 and 2.2.* Bottom line: the added resistor shouldn't be necessary, and if used, it may degrade supply rejection.

[3] Alas, you really can't depend on transistor data sheets to list a typical 1mA Vbe! Some are helpful, most are not. For a good example, BC547 and BC847 do list a typical Vbe of 660mV @ 2mA. Extrapolated to 1mA, then a typical working Vbe should be 18mV lower, or 642mV. Our test samples ran around 645mV on average. For others, test, test, and retest! A follow-on thought here is to make sure you have the correct part, *as to specific manufacturer*, as sometimes alternate sources might use different processes.