LEDs as DIY Audio Voltage References
(Part 1 of 2)

Walt Jung

Many modern LEDs have good utility as voltage references. For audio circuits, their virtues include low noise, low impedance, and many available voltages. While LED forward voltages (Vf) are generally low, this does have benefit. There is the ease of *series-stacking* multiple LEDs with (or without) conventional diodes, to create a net DC voltage. Nominal forward voltage drops for popular single LEDs are ~1.1V (infrared or IRLEDs), ~1.6V (red or RLEDs) and ~1.8V (green or GLEDs). *Note that the exact voltage will depend on the current!*

Why the Special LED Reference?

So, ***why*** do we need a special 2.5V (or other low voltage) audio reference? Well, we *do* need a special reference, *if low noise is paramount.* While the mV-level DC precision and very high stability of 1.2V and 2.5V silicon bandgap ICs is nice, bear in mind that this happens at a stiff cost in noise terms. In fact, readily available bandgap-based IC parts are very high in noise, vis-à-vis zener types. But zeners don't function at 2.5V, since they need ≥7V, just to function. Consequently, if you need a ~2V or other low voltage DC source for an audio reference, selection gets very tough indeed. You will likely need to make your own! Here is how to do just that!

Noise is a big deal for an audio reference, for sure. Adding further to potential confusion, one must always compare noise density levels[1] in terms of what they mean, *vis-à-vis the applicable full scale reference voltage*. For example, a TL431 2.5V reference with a 1kHz noise density of ~120nV/√Hz is much worse than a 7V reference with the same noise density – by nearly 3 times (since the two voltages have a ratio of 2.76). In fact, if we consider an actual 6.9V LM329 zener spec of around 70nV/√Hz, we will see this relevance of this point. The LM329 noise is referred to a full scale of 6.9V, and the TL431 is referred to a full scale of 2.5V.

To put all of this in perspective, one can easily compare different reference devices (or circuits) for noise, by normalizing their specified noise to 1V. In doing this, a 2.5V TL431 comes out as 120nV/√Hz divided by 2.5, or (48nV/√Hz) /V. And a 6.9V LM329 comes out as 70nV/√Hz divided by 6.9, or (10.1nV/√Hz) /V. Obviously, this is better, by a factor of almost 4.7/1. The moral of this story is that *a specified noise voltage density must not be evaluated on an absolute basis, but rather with regard to the normalized reference voltage.*

But how do we make a very low noise 2.5V reference? It turns out that a GLED in series with a single silicon diode can yield a DC drop around 2.5V, if run at just the right current. Here "right" means 1mA or greater, which is appreciably more current than any popular bandgap IC type. Nevertheless, this is a prerequisite for low noise. All of the bandgap ICs typically have core currents of a few tens-of-microamps, and it is these lower current levels that place a limitation on noise. Part of the problem is the noise gets amplified internally in generating the ~1.2V bandgap reference voltage.

Things are much better from a noise standpoint when we find a way to generate the reference voltage at a higher intrinsic level, so that internal noise isn't amplified. A GLED, which will have a typical forward voltage of 1.8 to 1.9V, is one means to this end. It has both the higher basic terminal voltage, plus the important bonus of low noise. These factors allow a green-LED-based reference to achieve noise levels about 0.025 that of the popular TL431 2.5V IC reference, i.e., on the order of 3nV/√Hz or less. Not to pick on the TL431 here, these principles also apply to most other bandgap reference ICs.

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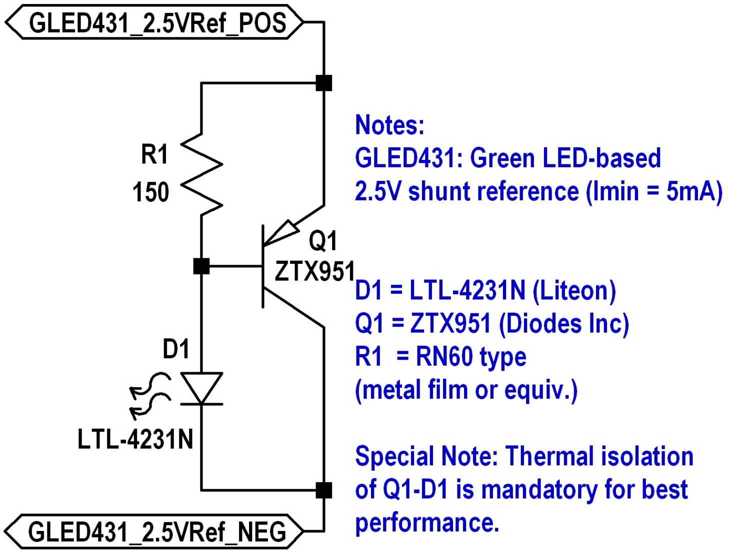
[1] Noise density specifies a noise level within a given bandwidth, i.e, 1nV/√Hz as one example.

The Original GLED431 2.5V Reference Circuit:

A first example LED circuit is shown in ***Figure 1***, the GLED431. [2] This circuit operates as a shunt type two-terminal reference, analogous to a zener, except for the much lower voltage. Either the POS or NEG node can be grounded. Also like a zener, the operating current is supplied externally, and *this current must be above a minimum threshold for correct functioning*. The circuit is intended as a low noise functional replacement for the 2.5V TL431, thus the GLED431 name.



Notes:
GLED431: Green LED-based
2.5V shunt reference (Imin = 5mA)

D1 = LTL-4231N (Liteon)
Q1 = ZTX951 (Diodes Inc)
R1 = RN60 type
(metal film or equiv.)

Special Note: Thermal isolation
of Q1-D1 is mandatory for best
performance.

Figure 1: ***A GLED431 Green-LED-Based 2.5V Shunt Voltage Reference***

This GLED431 circuit was originally built up on a two-pin header between 0.1" spaced conductors. This was used for the noise measurements below. Note that an SMD version is possible if a GLED such as the LTST-C230GTK is substituted for the LTL-4231N (both manufactured by Liteon). A direct substitute SMD version of the ZTX951 is not available. But, there are many medium power SOT23 types available, for example the MMBT4403.

A caveat here! It is important to note that such a synthesized LED-based 2.5V reference voltage will not be as stable with temperature as will a comparable bandgap IC. But it will not be terrible, either. In fact, the GLED431 circuit under discussion will drift on the order of -4mV/°C. So, for a 20°C ambient temperature swing, a 2.5V output voltage will change about 80mV. This is around 3.2% of the 2.5V full scale for this temperature range. Follow the encapsulation recommendations for best results on temperature stability.

But also note! Do not *expect to get similar results, if you use different parts, especially with the LTL-4231N LED.* However, all parts are readily available, so this isn't really a problem. Should you wish to *trim* the voltage, resistor R1 could possibly be used (in theory). R1 sets the current in D1, about 4mA, as shown.

Is it accurate? It is assumed that low-mV Vout accuracy for this reference *isn't* necessary. In fact, unless you take the trouble to trim it, you may see a Vout of 2.5V +/- 20mV. In practice it is possible that this won't matter much. It is worth noting that a TL431C has an initial tolerance ±55mV around 2.495V.

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[2] Walt Jung's GLED431 Article (2015)

Is it quiet? Yes, it most certainly is very quiet, measuring just over 3nV/√Hz for the prototype circuit using the sample 5 LEDs (column 6 of ***Table 1***). This is slightly more noise than the corresponding raw green LEDs. Note that the best noise performance is realized with appreciable current in Q1, which is to say equal to that in D1 (or more). Performance of this GLED431 circuit is noted in ***Table 1***, columns 6 and 7. But do note that any of these lowest level measurements with this system are somewhat fuzzy, due to the test setup's limited resolution. A 3nV/√Hz noise density for a 2.5V reference corresponds to a 1.2nV/√Hz / V performance.
The table also shows just how good the basic noise performance of a common GLED can be. These data were taken for Liteon LTL-4231N LEDs, but generally could also be applicable to other LEDs. It was taken from a sample of five such GLEDs, as listed vertically. Going left to right, columns 1 and 2 show the forward DC voltage drops (Vf), for currents of 1 and 5mA, for these five samples.

Note that the 1mA and 5mA Vf readings are shown in average, low, high and delta forms towards the bottom. Column 3 shows the Vf change for a 3 to 4mA shift in current (ΔVf for ΔI = 1mA), showing the diode's forward resistance in Ω, by Ohm's law.

Table 1: **Voltage and Noise Data for LTL4231N Green LEDs**
Basic GLEDs (Columns 1-5) and Within GLED431 2.5V Reg Circuit (Columns 6-7)

Vf(1mA)	**Vf(5mA)**	**ΔVf(3-4mA)**	**Vn(1mA)**	**Vn(5mA)**	**Vout(4mA)**	**Vn(2.5Vreg)**
1.8730	1.9730	0.0208	0.00283	0.00221	2.5142	0.00330
1.8740	1.9747	0.0207	0.00276	0.00208	2.5064	0.00320
1.8718	1.9724	0.0205	0.00279	0.00208	2.5009	0.00320
1.8721	1.9660	0.0199	0.00271	0.00210	2.5012	0.00310
1.8737	1.9727	0.0205	0.00269	0.00213	2.5028	0.00320
Vf(1mA) Five Sample Average (V):	**Vf(5mA) Five Sample Average (V):**	**ΔVf(3-4mA) Five Sample Average (V):**	**Vn(1mA) Five Sample Average (V):**	**Vn(5mA) Five Sample Average (V):**	**Vout(4mA) Five Sample Average (V):**	**Vn(2.5Vreg) Five Sample Average (V):**
1.8729	**1.9718**	**0.0205**	**0.00276**	**0.00212**	**2.5051**	**0.00320**
Vf(1mA) Five Sample Low (V):	**Vf(5mA) Five Sample Low (V):**	**Rs for Vf(3-4mA) Five Sample Average (Ω):**	**Vn(1mA) Five Sample Average (nV/√Hz):**	**Vn(5mA) Five Sample Average (nV/√Hz):**	**Vout(4mA) Five Sample Low (V):**	**Vn(5mA) Five Sample Average (nV/√Hz):**
1.8718	**1.9660**	**20.48**	**2.75600**	**2.12000**	**2.50090**	**3.20000**
Vf(1mA) Five Sample High (V):	**Vf(5mA) Five Sample High (V):**				**Vout(4mA) Five Sample High (V):**	
1.8740	**1.9747**				**2.5142**	
Vf(1mA) Five Sample Delta (V):	**Vf(5mA) Five Sample Delta (V):**				**Vout(4mA) Five Sample Delta (V):**	
0.0022	**0.0087**				**0.0133**	

A special note: Measurements similar to the above were also made for a wide range of other color LEDs; i.e., Red, Yellow, Orange and Amber units. In the interest of brevity, these aren't shown. However, it can be said that almost all of the LEDs tested for roughly comparable levels of noise. The GLED and RLED types have very low noise, and for all of these, the measurement numbers are considered conservative. White and blue LEDs did not do well in the few tests made.

Columns 4 and 5 (green) are most important to the noise topic. The upper cells show the measured voltage noise (Vn) within a basic 10kHz noise bandwidth, for forward DC currents of 1 and 5mA. Note that noise is substantially lower for the higher current, a point paramount to making a truly low noise reference circuit. Always run the LED (or Zener, if applicable) at the highest practical current for lowest noise.

The ***Table 1*** rightmost and lowest data cells show the noise averages for columns 4 and 5, as they are converted to a nV/√Hz equivalent reading. Or, in more simple terms, the 1mA and 5mA operating current average voltage noise density for the 5 samples. While in both cases the noise measurements are very low (well below 3 nV/√Hz) some caveats are in order. *These levels of noise are pushing the test setup resolution!* Indeed, the test set with a dummy 20Ω source resistor shows a residual noise of around 2 nV/√Hz (slightly less). Thus, the actual noise of these GLEDs under test are most likely lower than the table numbers indicate. What isn't so certain is exactly how much. But, exact isn't critical to the basic point — the noise is in the desired ballpark! The important conclusion is that a GLED type does offer very low noise, and this noise is a very small percentage of a relatively large DC voltage (the ~1.87V of column 1).

Finally, it should be appreciated that the general topology as shown in ***Fig. 1*** can also be used with a wide variety of Q1 transistors. Other transistors tested were the ZTX550 and BC557B types (TO92 or equivalent). But, as noted above, many SMD versions abound and can also be suggested. In cases of high capacitance Q1 types, a small shunt capacitor from POS to NEG may be appropriate for stability, in a range of 0.1 to 1μF. Testing carefully here is mandatory.

Finally, a key point which may or may not be obvious. Note that since the Q1 amplifier acts to drive D1 with a constant current of Vbe/R1, a wide variety of other devices can be used in the D1 position — not just LEDs. These include higher voltage zeners, and various other LEDs, either singly or stacked. For example, if a 6.2V zener such as a 1N5234B is used, a nominal 6.8V reference results, one with good to excellent TC (unlike the higher TC of the GLED431 circuit). The circuit generally works to produce a buffered Vout as: 1) equal to Vbe(q1) + Vz (D1) (with D1 = zener), or 2) Vbe(q1) + Vf (D1) (with D1 = LED).

Further Noise Basics:

When measuring and calculating wideband noise, it must be appreciated that multiple noise sources do not add directly when combined. We know that for the case of Vf of series LEDs, one can simply sum the individual Vf DC voltages, as in 1.6V + 1.8V results in a net 3.4V. This is of course quite straightforward.

But, *uncorrelated noise voltages add in Root-Sum-Square (RSS) fashion* — not directly! So, if we have two noise sources Vn1 and Vn2 expressed as noise densities, the total net noise is Vtotal = √[(Vn1^2) + (Vn2^2)]. This is of course the RSS equivalent for Vn1 and Vn2. Example: if Vn1 and Vn2 are both noise densities of 2nV/√Hz, then Vtotal is √[2^2 + 2^2] or, Vtotal = √8 = 2.8nV/√Hz.

Obviously, this is much less than a simple sum. Likewise, if we have four such noise densities, each one 2nV/√Hz , then Vtotal = √16 = 4nV/√Hz. Here, a useful rule-of-thumb is that noise will double with four equal level noise sources, since √4 = 2. Note that this RSS addition property works to make combining multiple LEDs in series quite useful, as the DC voltages up add faster than do the noise voltages. In effect, one realizes a net gain in lower *normalized noise*, when the RSS equivalent is referenced to a higher DC level.

In practice, the RSS addition property can allow noise to be managed quite effectively when dealing with multiple noise sources. This will be more apparent within the next section on series-stacked LEDs and the resulting noise.

A Series-Stack LED-Zener Equivalent

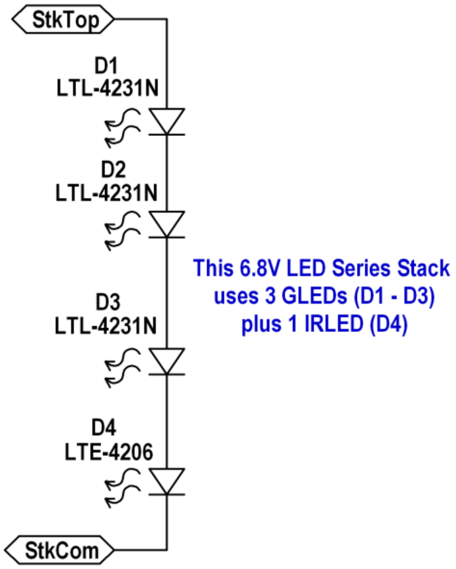
To synthesize a “LED-zener”, look at ***Figure 2***. This example setup series-connects two or more LEDs so that their summed forward voltages are close to what is needed. As an example, 3 GLEDs (~1.8V) plus 1 IRLED (~1.1V) sums to 6.5V for DC. In practice you might see more (or less), depending on the exact current.

Using hand-made SPICE models, the ***Fig. 2*** circuit clocked in at almost exactly 6.8V, with If = 5mA. What we have is essentially an LED-zener equal to an 1N52345B, with notable differences. The LED-zener will excel for noise, as compared to an approximate 20nV/√Hz for a real 1N5235B at the same current. If we assume a 2nV/√Hz noise for each of the D1/D4 diodes, the RSS net for ***Fig. 2*** noise would then be 4nV/√Hz— about 5 times as good! Note the DC voltage/stability of the LED-zener is worse than a 1N5235B, so we have tradeoffs.

The LEDs of ***Fig. 2*** are Lite-On 3mm leaded LEDs, as are typically used in through-hole assembly. But similar versions have also been assembled with SMD parts, such as Lite-On LTST-C230GKT GLEDs. These were mounted on a small piece of prototype PCB for testing and performed like the leaded types. Note that almost any combination of forward biased LEDs and regular diodes (1N4002 etc.) can be used in such a series-stack. This holds as well for lower voltage zeners, as might be suitable (BZX84C3V3, BZX84C2V7).
Gerhard Hoffman’s DIYAudio work is required reading for serious audio builders. Highly recommended! [3]

The resulting ***Fig. 2*** LED-zener will have a poor but not terrible temperature coefficient. If each diode drifts 2 mV/ºC, the net for four is 8 mV/ºC. But against the 6.5V, this is a drift of ~0.12%//ºC, which is probably OK for small temperature shifts. It is also better than the drift of 10 series 1N4002s, since the basic single-LED voltages are so much higher vis-à-vis the 0.6V of a 1N4002.

As noted, the noise levels LEDs produce is exceptionally low, in some it may be just a few nV/√Hz. For a GLED the nominal forward DC voltage is in the range of 1.8 to 1.9V (again, current dependent). Thus if a GLED part has a 2 nV/√Hz noise with a forward voltage of 1.8V, the normalized noise with respect to the DC voltage would be stated as ~1.1 nV/√Hz per DC volt. To get a perspective on this, compare it to an LM329 with a 70 nV/√Hz noise, and a DC voltage of 6.9V — the normalized noise is ~10.1 nV/√Hz per DC volt. For the example of ***Fig. 2*** LED-zener the normalized noise would be about 4nV/√Hz/6.8V, or around 0.6nV/√Hz, which is quite superior.



This 6.8V LED Series Stack uses 3 GLEDs (D1 - D3) plus 1 IRLED (D4)

Figure 2: **A Series-Stack example of 3 GLEDs and 1 IRLED acts as if it were a single ~6.8V LED-Zener diode (right).**

Treat terminal “StkTop” as a single diode anode, and “StkCom” as a cathode. The number of LEDs can vary, as can forward biased standard diodes (1N4002, etc.), as may be required to mimic a given Vf for the Series-Stack.

The dynamic Z will be higher than that of a conventional Zener, but the noise will be appreciably less... see text.

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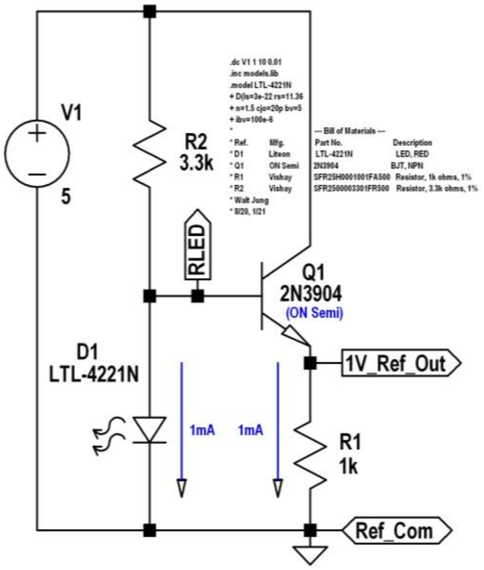
[3] Gerhard Hoffman's DIYAudio discussions on LEDs and zener diode noise

The Pete Lefferts LED-Based Current Source:

In 1975 Pete Lefferts of National Semiconductor published a type of current source based on the forward voltage of an LED as a reference voltage, working against the Vbe of a BJT. [4] He showed both 2N2905 PNP and 2N2222 NPN forms of this current source (shown as his Figures 1 and 2, respectively). The LED was a National NS5027, a red type. The basic innovation of the Lefferts source is that the negative TC of the LED Vf tracks the Vbe of the BJT (PNP or NPN), both being on the order of -2mV/ºC. The allows the temperature characteristic of the BJT output current to approach a flat nature, i.e., independent of the local environment.

A modern example of the Lefferts current source is shown in ***Figure 3***, as configured for a 1mA current, operating from a 5V supply. It also produces a very stable 1V output.



```
.dc V1 1 10 0.01
.inc models.lib
.model LTL-4221N
+ D(Is=3e-22 rs=11.36
+ n=1.5 cjo=20p bv=5
+ ibv=100e-6
*
* Ref.   Mfg.
* D1     Liteon
* Q1     ON Semi
* R1     Vishay
* R2     Vishay
* Walt Jung
* 8/20, 1/21
```

--- Bill of Materials ---

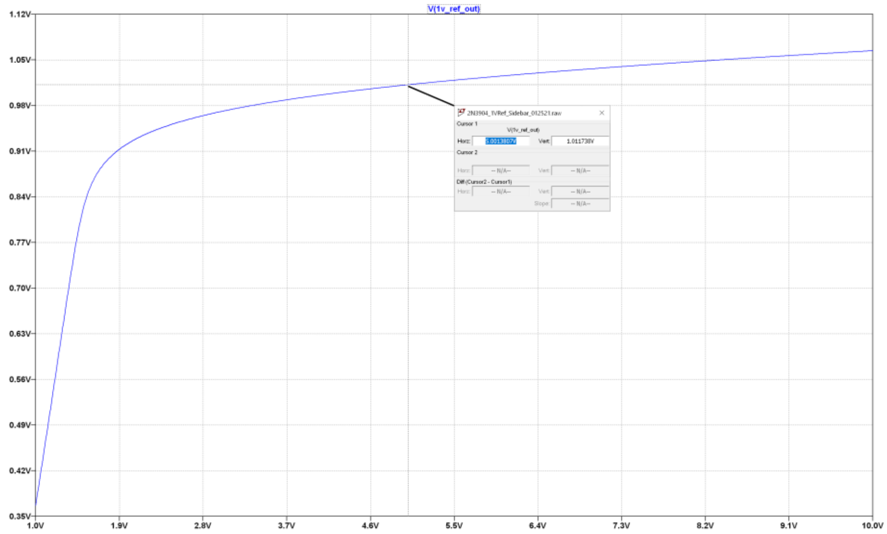
Part No.	Description
LTL-4221N	LED, RED
2N3904	BJT, NPN
SFR25H0001001FA500	Resistor, 1k ohms, 1%
SFR2500003301FR500	Resistor, 3.3k ohms, 1%

Figure 3: **An NPN/RLED based Lefferts type current source designed for 1mA , operating from 5V (right).**

R2 sets up the current in the RLED D1 to 1mA, as shown with a 5V supply. This creates a nominal 1.6V at the RLED terminal. NPN Q1, a 2N3904, has a ~0.6V Vbe, thus the 1V_Ref_Out terminal will bias up to a voltage close to 1V, with 1mA flowing in R1/Q1.

The circuit can be used either as a current source, loaded in the collector path of Q1, or as a simple 1V reference, referred to common. Also (but not shown) are PNP-based negative output versions, using a 2N3906 Q1 type.

The ***Fig. 3*** circuit is deceptively simple, yet is still capable of very high performance. Attention must be paid to selection of both the RLED and the NPN. The types shown have a fortuitous synergism and can produce a 1V output within a few mV. Use the specified D1-Q1 parts coupled together for best thermal stability.



Horz: 5.0013807V Vert: 1.011738V

Horz: -- N/A-- Vert: -- N/A--

Horz: -- N/A-- Vert: -- N/A--

Slope: -- N/A--

Figure 4: **A graph of the 1V reference output from *Fig. 3*, as depicted by SPICE (right).**

Since this is simply a SPICE simulation, any such circuit must be bench-verified.

Also, the *Fig. 3* circuit is best suited for fixed input voltages.

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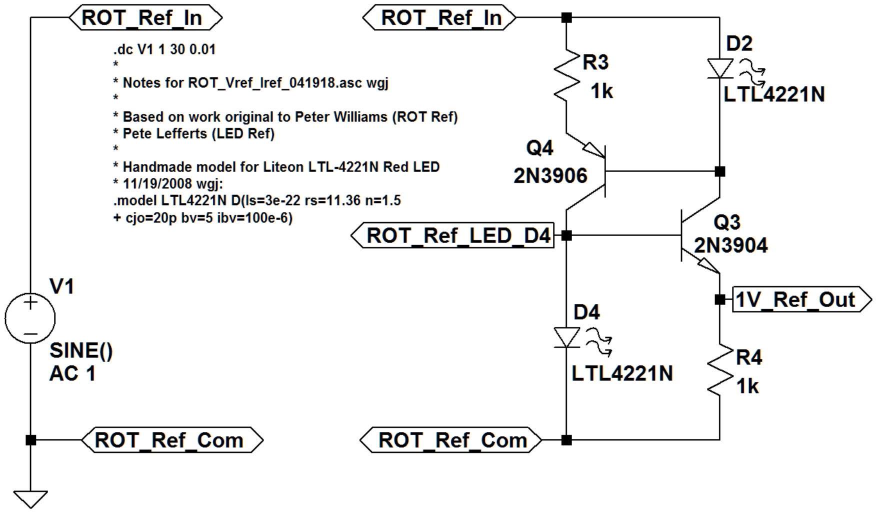
[4] Peter A. Lefferts, “LED Used as Voltage Reference Provides Self-Compensating Temp Coefficient,” *Electronic Design*, Feb. 15, 1975, pp. 92.

The Ring-of-Two Voltage/Current Reference Circuit:

Figure 5 is what has been called the "Ring-of-Two" (ROT) reference, because it is a positive feedback loop with complementary sub-circuits feeding one another. In other words, a closed ring of two stages. What is fascinating about the circuit is that it can be used as both a current or voltage reference, with low TC and good-to-great supply immunity. Plus, the simplicity of only six total parts!



```
.dc V1 1 30 0.01
*
* Notes for ROT_Vref_Iref_041918.asc wgj
*
* Based on work original to Peter Williams (ROT Ref)
* Pete Lefferts (LED Ref)
*
* Handmade model for Liteon LTL-4221N Red LED
* 11/19/2008 wgj:
.model LTL4221N D(Is=3e-22 rs=11.36 n=1.5
+ cjo=20p bv=5 ibv=100e-6)
```

***Figure 5:* This ROT LED-biased reference circuit can be used as either a voltage or a current reference, with either option capable of very high performance.**

As a Vref, ground ROT_Ref_Com and take a stable 1V from 1V_Ref_Out. As an Iref, take a 2mA current source from ROT_Ref_Com.

Alternately, ground the ROT_Ref_Com terminal and take a 2mA current sink from ROT_Ref_In.

In the ***Fig. 5*** schematic, extracted from an LTSpice simulation, the 2N3904/3906 transistors and related parts form the ROT reference circuit. This basic scheme was first published by Peter Williams in the UK.[5] In the original Williams circuit zener diodes were used in the D2/D4 locations, and the primary application was as a voltage reference.

Backup up a bit, note that the ***Fig. 3*** Lefferts circuit comprises one half of a ROT reference (for example Q3, R4 and D4 of ***Fig. 5,*** as compared to their ***Fig. 3*** counterparts). The beauty of the basic Williams ROT configuration is that it effectively locks out sensitivity to the supply voltage used. As previously noted, the more simple circuit of ***Fig. 3*** is more sensitive to supply changes, since the R3 current changes with supply voltage. Shortly afterwards his 1975 LED-based source, Pete Lefferts incorporated the low TC LED-biased scheme within a Peter Williams type ROT circuit. [6] It is this ROT reference that is reprised here as ***Fig. 5.*** It incorporates the best of both, which is worth noting. And, the topology is able to work down to very low voltages, as noted in the second Lefferts article. In fact, it is generally able to operate from voltages of approximately 2*Vf of the LED used.

Just as shown, the circuit runs with 1mA of current per side, or 2mA total. This of course can be re-scaled to other current levels. Or, alternate (but still complementary) transistors can be used. With the types shown and RED LTL-4221 LEDs for D2/D4, the 1V_Ref_Out output was found to be within +/-10mV on the bench. The operating current is set as two equal components, one by 1/R3 and one 1/R4. Each resistor has 1V across it. The entire circuit should be encapsulated for best thermal stability and isolation from air currents, with the transistor-LED pairs D2 - Q4 and D4 - Q3 placed close to one another.

A potential caveat of this circuit is reliable startup. For inputs below the Vf potentials of the LEDs, they appear as high impedances, thus loop gain is very high, and any transistor leakage will tend to kick the loop into a rapid

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[5] Peter Williams, “Ring-of-Two Reference,” *Wireless World,* July 1967, pp. 318-322.

[6] Pete Lefferts, “Variable Slope Current Source Starts at 2.5V,” *EDN*, Nov. 5, 1975, pp. 100.

transition, which ends in a latch mode with both LEDs ON. In this final state the loop gain is much lower, and the circuit is then quite stable.

For some cases, an aid to startup might be needed. A simple high value resistance of around 1megΩ between the Q3/Q4 bases will suffice for this. The value here isn't critical at all, so long as the input voltage change is small. Such is the case where the reference is used within a circuit as the main Vref for a 3.3 or 5V Super Regulator. Of course, the regulator must then employ a low voltage op amp, i.e., one suited for inputs of 1V.

For the two circuits of ***Fig. 3*** and ***Fig. 5***, two simply outstanding virtues are the inherent low TC as discussed above, and also very low noise. The noise of ***Fig. 5*** was found to be only a few nV/√Hz, as measured for the 1Vdc reference level at 1V_Ref_Out**.**

SPICE simulation performance of the ***Fig. 5*** circuit for both voltage and current modes is shown in ***Figure 6***, with a wide range of input voltage (Δ = 28V).

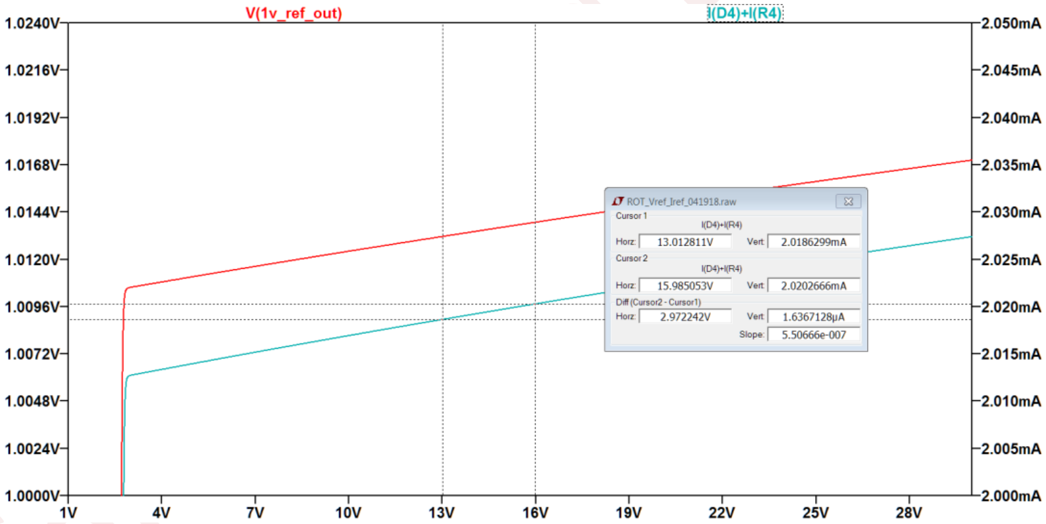
ROT_Vref_Iref_041918.raw
Cursor 1
I(D4)+I(R4)
Horz: 13.012811V Vert: 2.0186299mA
Cursor 2
I(D4)+I(R4)
Horz: 15.985053V Vert: 2.0202666mA
Diff (Cursor2 - Cursor1)
Horz: 2.972242V Vert: 1.6367128µA
Slope: 5.50666e-007

***Figure 6:* The ROT LED-biased reference circuit has very high performance. Here 1V_Ref_Out is depicted by the RED trace (left scale).**

As a 2mA current source, performance is shown by the I(D4)+I(R4) AQUA trace (right scale). The current sensitivity to input change is 0.55uA/V, roughly equivalent to a 2 megohm impedance.

As noted, the input voltage threshold for circuit operation is quite low. In ***Fig. 6***, the V/I outputs are fully settled for inputs above 3V. This is primarily due to the relatively low threshold of the RLEDs used (~1.6V). IRLEDs can lower this threshold even further since they have a ~1.1V Vf.

Some caveats on the above:

These circuits were developed several years back. In some cases, even better parts might be more suitable today. For example, the use of SMD devices, which should help temperature stability. As for general validity, be assured it has all been built and tested.

For performance, the absolute levels of noise as quoted might be questionable, given the limitations of the setup used. Nevertheless, basic principles are still sound, that is higher currents in a GLED (or RLED) will result in lower noise. And most importantly, the RSS addition of multiple LED (or other) noise sources helps greatly to reduce net noise. It should be appreciated that these techniques require some advanced skills on the part of the DIY builder, so take heed.

Finally, see the Part 2 article, "***A 1V Reference with Mirrors"*****,** and good luck!