Two (or 2.5) Easily Constructed High Performance Audio Voltage References

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From my recent web site correspondence, there is still strong general interest in voltage regulators for audio. This interest extends to the details of operation within the regulator circuitry, such as for example higher performance from the voltage reference. This note addresses these queries, specifically on voltage references, with two or more new examples.

People ask often about lower noise references, particularly for lower voltages such as 2.5V for digital circuits. Lower noise is also a virtue of higher voltage references, such as zener-based types. Finally, they also ask about all-SMD parts, for minimizing final circuit size. All such things are possible. I set out to develop a couple of new higher performance (for noise at least) reference circuits. These are described below, in two parts.

Part 1: A Green-LED-Based 2.5V Shunt Voltage Reference

So, ***why*** do we need a special 2.5V audio reference? We already have TL431's and many other inexpensive, readily available *bandgap* ICs. Note that these are so named as *"bandgap-based*", for the *silicon bandgap voltage*, which is typically around 1.20 to 1.25V for most such references. This internally generated voltage can be scaled (either internally or externally) to standard output voltages. For example, 2.5V, 5.0V, etc are typical. The TL431 scales to an external voltage of nominally 2.500V, as seen in operation between the reference (REF) and anode (ANODE) terminals of the part.

Ah yes, we do need a special reference, *if low noise is considered important.* While the mV-level DC precision and very high stability of 1.2V and 2.5V silicon bandgap ICs are very nice, bear in mind that this happens at quite a high cost to noise. In fact, all of the available bandgap-based IC parts are very high in noise, vis-a-vis zener types. Unfortunately though, the zener parts don't function at all for 2.5V, since they need more than 7V applied to function. As a consequence, if you need a ~2V or other low voltage DC source for a low noise audio reference, selection gets very tough indeed. You will likely need to make your own.

Adding further to potential confusion, one must always compare noise density levels in terms of what they mean, *vis-à-vis the applicable full-scale reference voltage*. For example, a TL431 2.5V reference with a 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 120nV/√Hz 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 about 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 with regard to the actual reference voltage.*

So just how do we make a very low noise 2.5V reference? It turns out that a green LED diode 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 around 0.5 - 1mA, which is appreciably more current than that of most 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 bottom-line limitation on noise, which gets amplified internally in the process of 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 doesn't get amplified. A green LED, which will have a typical forward voltage of 1.8 to 1.9V for currents around 1mA, is one means to this end. It has both the higher basic terminal voltage, plus the important bonus of very 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. We'll use the TL431 as a point-of-reference for this discussion, but these general principles apply to other bandgap ICs with similar design tradeoffs.

A TL431 has a voltage noise density above 100nV/√Hz at 1kHz, and more than this at lower frequencies (see device data sheet Fig. 11). Ironically, the data sheet calls out "Low Output Noise" within the feature table, but there is no listing for noise in the electrical characteristics tables. Bear in mind this point-- the strong suit of this (and other) bandgap-type ICs lies not in noise performance, but in the high initial DC accuracy, and excellent overall stability. In these latter regards they offer maximum bang-for-the-buck, unquestionably. But for low noise, you need to look elsewhere,

Table 1 below shows just how good the basic noise performance of a representative green LED can actually be. These data were taken for the Liteon LTL-4231N, but could just as easily be applicable to others. The data was taken from a sample of five such green LEDs, 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 the 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 voltage change for a 3 to 4mA shift in current (ΔVf for ΔI = 1mA), which in turn shows the diode's forward resistance (Ω).

Columns 4 and 5 are most important to the topic at hand, noise. The upper cells show the measured voltage noise within a basic 10kHz noise bandwidth, for forward DC currents of 1 and 5mA. Note that the measured noise is substantially lower for the higher current.

The **Table 1** rightmost and lowest data cells show the noise averages for columns 4 and 5, as converted to a nV/√Hz equivalent reading. In more simple terms, the 1mA and 5mA operating current average voltage noise density for the 5 samples. While in both cases the noise measurement is very low (apparently well below 3 nV/√Hz) some caveats are in order for best interpretation. *These low levels of noise are actually pushing the test setup resolution!* Indeed, the test set with just a dummy 20Ω resistor used as a source shows a residual noise of around 2 nV/√Hz. Thus, the actual noise of these green LEDs under test are most likely lower than the table numbers indicate. What isn't so certain is exactly how much. But, exactly isn't critical to making the point. This low a noise is within the right ballpark!

So, the important conclusion is that this green LED type does offer very low noise, and this noise is a very small percentage of a relatively large DC voltage (the 1.8 - 1.9V of column 1). These two factors make it a great candidate for a low noise 2.5V reference.

Table 1: Liteon LTL-4231N Green LED DC / AC Characteristic Performance

Vf(1mA)	Vf(5mA)	ΔVf(3-4mA)	Vn(1mA)	Vn(5mA)
1.8730	1.9730	0.0208	0.00283	0.00221
1.8740	1.9747	0.0207	0.00276	0.00208
1.8718	1.9724	0.0205	0.00279	0.00208
1.8721	1.9660	0.0199	0.00271	0.00210
1.8737	1.9727	0.0205	0.00269	0.00213
Vf(1mA) Five Sample Average (V) is:	**Vf(5mA) Five Sample Average (V) is:**	**ΔVf(3-4mA) Five Sample Average (V) is:**	**Vn(1mA) Five Sample Average (V) is:**	**Vn(5mA) Five Sample Average (V) is:**
1.8729	**1.9718**	**0.0205**	**0.00276**	**0.00212**
Vf(1mA) Five Sample Low (V) is:	**Vf(5mA) Five Sample Low (V) is:**	**Rs for Vf(3-4mA) Five Sample Average (Ω) is:**	**Vn(1mA) Five Sample Average (nV/√Hz) is:**	**Vn(5mA) Five Sample Average (nV/√Hz) is:**
1.8718	**1.9660**	**20.48**	**2.75600**	**2.12000**
Vf(1mA) Five Sample High (V) is:	**Vf(5mA) Five Sample High (V) is:**			
1.8740	**1.9747**			
Vf(1mA) Five Sample Delta (V) is:	**Vf(5mA) Five Sample Delta (V) is:**			
0.0022	**0.0087**			

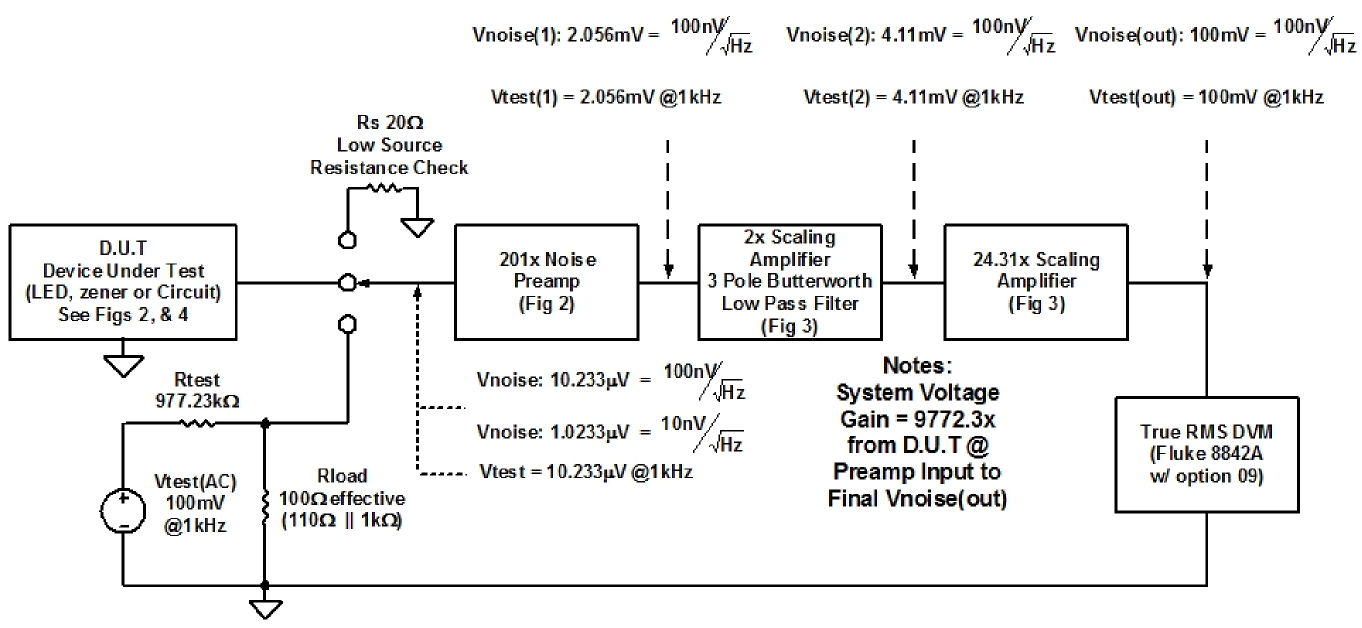
Note: Measurements similar to the above were made for a wide range of other color LEDs, such as Red, Yellow, Orange and Amber units. Data like the above was also taken for 5 samples for these LED colors as well (20 more samples, total). In the interest of brevity, these data aren't shown explicitly. However, it can be said that all of the LEDs tested show roughly comparable levels of noise. This is definitely a good thing to know!

To measure these very low levels of noise, the noise measurement system of **Figure 1** is used. The key performance points this system provides are: a defined *noise bandwidth*, an easily verified *calibrated gain*, *convenient setup* over a range of DUT test current(s), and *immunity against transient overload damage.*

The setup is based on a total system voltage gain of ~9772 times, within a noise bandwidth of about 10kHz. The gain scaling is such that a noise density of 100nV/√Hz from the DUT produces at the output 100mV AC(rms), which is displayed on a true RMS DVM. This allows interpretation in terms of equivalent noise from the source, i.e., 10nV/√Hz corresponds to 10mV AC(rms), etc.

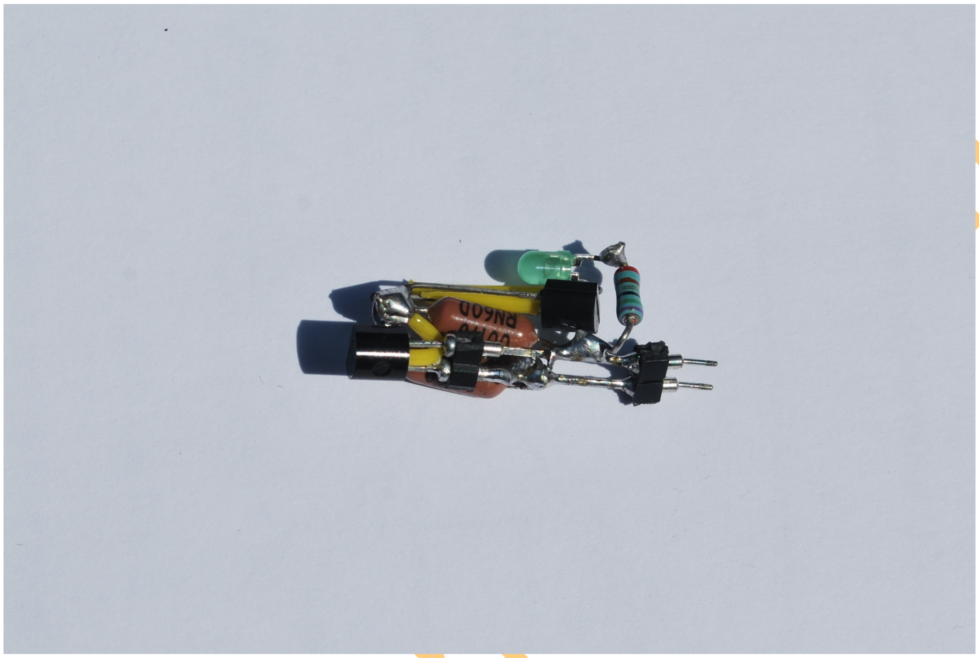
The DUT is placed in a test circuit where a clean DC test current drives the LED (or circuit) over a 1-5mA range. With a 201x gain in the first stage, the residual system noise limits the lowest measurement levels to around 3-5nV/√Hz (more on this below).

Figure 1: Noise Measurement System Used for Reference Device or Circuit Characterization



The first example reference circuit test prototype is shown in **Photo 1.** This is a circuit built up on a two pin header between 0.1" spaced conductors. At the left can be seen the rear of a PN2222A, with the Green LED and rear of a 2N3906 towards the right, top. This example uses a 75Ω trim resistor R3, as can be noted soldered between the LED and ground pin. This will be more obvious with the schematic, which is shown next.

Photo 1: A Green-LED-Based 2.5V Shunt Voltage Reference Prototype



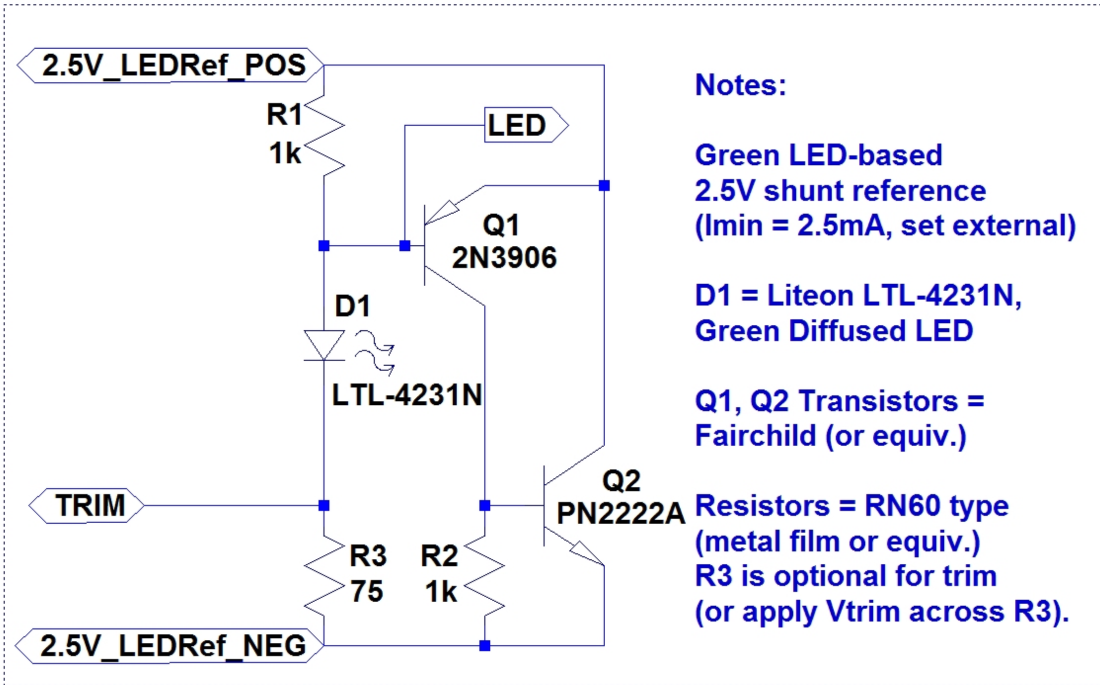
It is important to note that such a synthesized LED-based 2.5V reference voltage won't be as stable with temperature as will a comparable bandgap IC. But it won't be so terrible, either. In fact, the green LED type of circuit under discussion will drift on the order of -4mV/°C. So, for a 20°C ambient 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.

An example circuit corresponding to the **Photo 1** prototype above is shown next, in **Figure 2**. This circuit operates as a shunt type two-terminal reference, analogous to a zener diode (except for the much lower voltage). Or, functionally just like the TL431 with CATHODE and REF terminals common. 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 of **Fig. 2** drives the D1 green LED with a constant current of about 660µA, as established simply by the Vbe of PNP Q1 and the R1 value. Thus the output voltage is simply $Vf_{(D1)}$ plus $Vbe_{(Q1)}$, which adds up to around 2.5V when everything is set correctly. Actually slightly less than 2.5V is typical, by about 40-50mV.

Note! Don't expect to get similar results if you use different parts, especially the LTL-4231N LED. However, all parts are readily available, so this isn't really a problem.

Figure 2: A Green-LED-Based 2.5V Shunt Voltage Reference Schematic



Q2, an NPN second stage, provides additional gain for the active diode, which aids in lowering dynamic impedance. Note that this entire circuit has only 5 (or 6) parts, and none are super critical (except as noted).

Should you should wish to *trim* the voltage, a R3 is used. With R3 = zero, the output is lower than an ideal 2.500V, measuring around 2.460V. With R3 = 75Ω, it is slightly over, around 2.512V. These voltages were measured on a couple of test prototypes, but your mileage may vary. Note that should you want to set things exactly, a 100Ω trimmer for R3 can be used. Allow a few minutes of warm up before making adjustments.

Is it accurate? It is assumed that mV type 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 +/- 50mV or so. Note that you can help things greatly here, by preselecting D1. R2 sets the current in Q1 to be nominally equal to that of D1, i.e., 660µA, as mentioned. Should you really wish to get fancy, note that you can also adjust the output by applying a voltage across R3, as noted.

On the plus side, bench measurements and simulations show a dynamic impedance of ~1.3Ω for currents of 2.5mA or more. This aspect of performance is comparable to that of many bandgap IC references— for example the TL431 has a typical 0.2Ω impedance.

Is it quiet? Yes, it certainly is, measuring around 4nV/√Hz for the prototypes. This is slightly more noise than a raw green LED (Table 1), but any lowest level measurement with this system is somewhat fuzzy, due to resolution. Note that a hypothetical 4nV/√Hz noise density for a 2.5V reference corresponds to a 1.6nV/√Hz / V performance.

The circuit prototypes were built using ordinary TO-92 transistors and RN60 type film resistors. The preferred Fairchild parts specified are available in both leaded and SMD form, so the circuit can easily be miniaturized using SMD resistors and transistors (i.e., MMBT3906 vs. 2N3906, etc).

Part 2: A Zener-Based 6.9V Shunt Voltage Reference

The simple and effective shunt mode regulator circuit of **Fig. 2** can also be applied with other reference parts in place of the green LED. **Figure 3** below is a *zener-based* shunt voltage reference, as targeted for a nominal 6.9V terminal voltage. It uses a 6.2V zener for D1, a 1N5234B or its equivalent, in conjunction with the one Vbe of Q1, a 2N3906. As noted, this is very similar to the 2.5V LED reference of **Fig. 2,** in terms of the basic topology.

In this case the 6.2V of D1 adds to the Vbe of Q1, to produce 6.9V. This the basic system concept of the industry standard [LM329 reference](). Although the circuit here is entirely different than that within the LM329, it follows some of the same concepts. The reference zener is driven with a fixed stable current, which is independent of the total shunt current due to the use of buffering. The positive TC of the D1 6.2V zener nominally cancels the negative one Vbe TC of the Q1 amplifying transistor.

Figure 3: A "PM329" Zener-Based 6.9V Shunt Voltage Reference Schematic

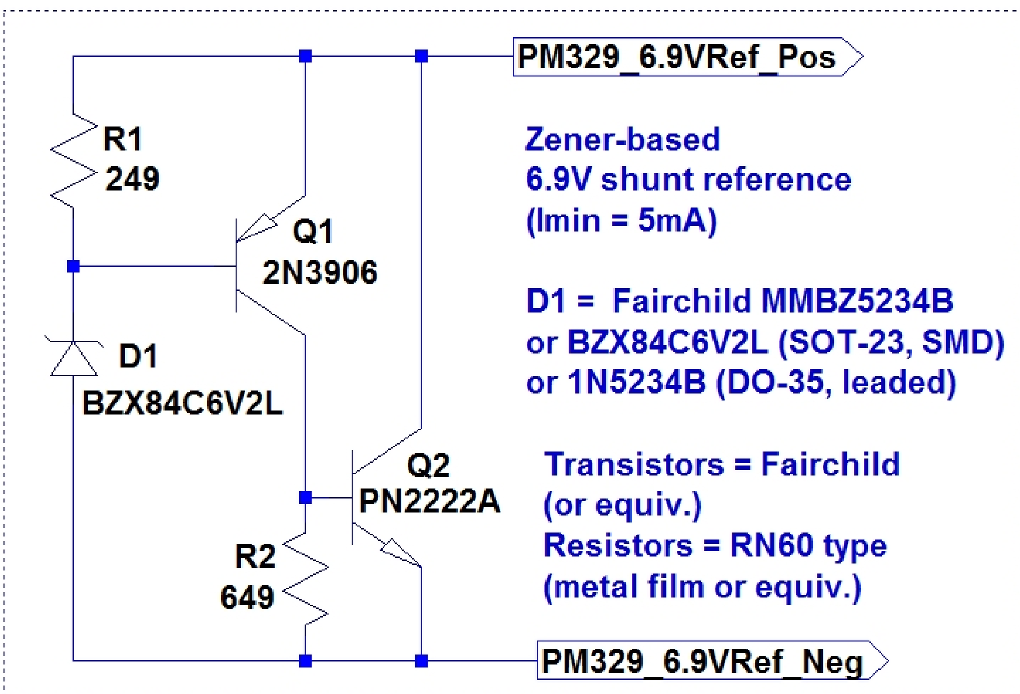


Photo 2: A PM329 Zener-Based 6.9V Shunt Voltage Reference Prototype

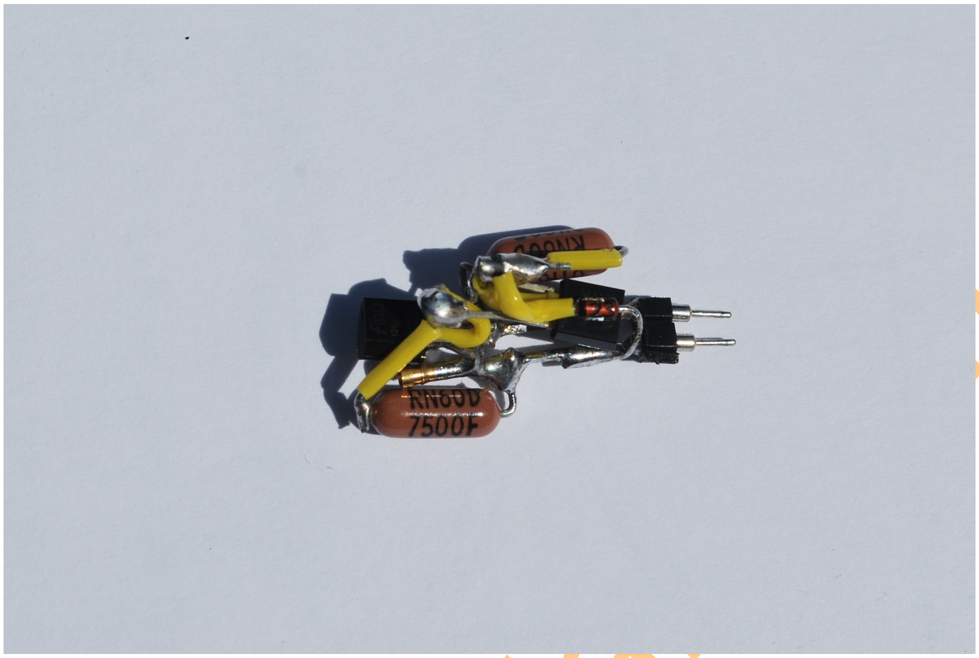


Photo 2 shows the zener-based shunt regulator, built in a fashion just like **Photo 1**. Here, the D1 1N5234B zener can be noted towards the right foreground, with the Q1 2N3906 immediately under and in contact with this diode. It is helpful towards overall DC stability that these two parts be thermally mated and isolated from air currents.

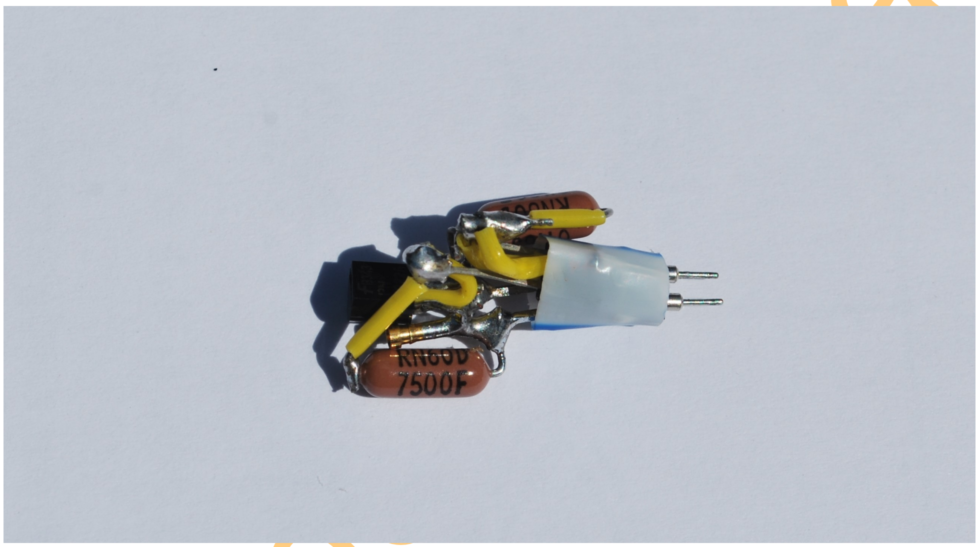
Photo 3: Output from the PM329 Zener-Based 6.9V Shunt Voltage Reference Prototype

Photo 3 shows the output from this reference as displayed on a DVM with 4.5 digit resolution (20V range). Once warmed up and stable, the voltage should be stable to about a mV or less. An actual performance point not so obvious from these two photos is the

relative stability of the **Fig. 3** circuit. *This depends upon the physical form, as well as electrical factors.* For example, the two voltages produced by D1 and Q1 should be held stable, by *isolating them as a pair*. This can be rather easily achieved by sliding a section of a plastic soda straw over them, with the straw sized to fit snugly.

An example of this is shown in **Photo 4**. This is the same circuit as shown in **Photo 2**, but with the straw section now covering D1-Q1. It is this form used for **Photo 3**, running at 5mA. Once proper operation has been verified, some RTV silicone can be used to make the setup even more stable and solid.

Photo 4: The PM329 Zener-Based 6.9V Prototype with D1-Q1 Thermal Isolation



Is it accurate? This circuit can be trimmed if desired, along the lines of the **Fig. 2** LED circuit, by using a resistor in series with D1 (not shown). It may be better from a system standpoint to let the voltage be what it may, as it will vary with the zener tolerance. If needed, trimming can be done via the divider of the regulator in which the circuit is used.

Is it quiet? Noise performance, while not quite as spectacular as that of the green LED counterpart, is still very impressive. This is due to the relatively high current in the zener, here around 2.6mA with R1 at 249Ω. By way of contrast, the LM329 runs the reference zener around 250µA, and achieves a minimum bias current threshold under 1mA.

The higher 2.6mA zener current pays off in terms of noise, as the **Fig. 3** circuit measures around 22nV/√Hz, with relative independence of current once the threshold is met. A hypothetical 22nV/√Hz noise density for a 6.9V reference corresponds to a 3.2nV/√Hz / V performance. This is roughly three times better than the LM329 spec of 70nV/√Hz.

To Be Continued: Part 2.5, system comments, acknowledgments, etc.