# LTC2387 drivers part III

## Trans-impedance amplifier/driver

This is unabashedly a classic case of what marketing calls "a solution looking for a problem". It is an example of how the full SNR of the LTC2387 may be realized for a real world signal. Most signals originating in low level circuitry, in sensors, or in the real world, will require significant gain to develop 8V p-p differential, in which case 90+ dB SNR will be elusive. This example is suited to high power optical applications. The circuit described in this note is a composite trans-impedance amplifier followed by a common mode servo similar to that described in part II of this series and in "Near Noiseless ADC Drivers for Imaging", LT Journal July 2013.

With 10K trans-impedance gain, this example achieves nearly transparent operation, as far as SNR is concerned, producing a noise floor 95.1 dB below a would-be full scale bipolar sinusoid. I state this in this peculiar fashion for a reason. Although the trans-impedance gain stage is 10K, it is followed by attenuation in the common mode servo, reducing a 0-10V excursion to 0-4V. Although it produces the lowest noise floor of the drivers published in this series, it must be recognized as intended primarily for unipolar signals. Many trans-impedance amplifier implementations that I have witnessed, employed a great deal of complexity, to introduce as close as possible to 50% full scale offset, in an attempt to use the entire input range of an ADC; usually adding noise, non-linearity, board area, cost, weight, time to market, failure modes and power consumption to the design. Instead, they could often simply use a higher resolution ADC to get the same dynamic range.

In this case at least, arguably the greatest benefit in throwing away half the input range is the low 1/f region at bipolar zero. This ADC has very little 1/f noise at bipolar zero, but at full scale, 1/f noise in the reference comes into play. This design also has low offset and offset drift, yet provides low distortion out to several MHz. Having low 1/f noise, or even low noise broadband, at high levels of illumination seems pointless as most light sources appear to be noisy well beyond the light itself, which is noisy due to shot noise. The noisy nature of light becomes more apparent at higher trans-impedance gain, perhaps making the loss of SNR at high trans-impedance gain a little easier to accept. Certainly solid state lasers are very noisy. In addition, APDs, and photomultipliers are very noisy under illumination as even ideal multiplication of photons would produce amplification of the shot noise along with the signal. In addition, the multiplication is not ideal. The feature of low noise in darkness would be important for high dynamic range pulse stretching applications where a very a very short pulse results in minimal amplitude that would be masked by noise.

So, restating the SNR statement: Viewed as a unipolar ADC, the design achieves 89.1 dB SNR. Still not bad.

In actual fact, the amplifier is not quite unipolar. There is enough usable range below bipolar zero, in the population shown in figure 2, to accommodate a signal power to about -15dBfs. This is hopefully enough to accommodate AC coupled noise or interferers, diode leakage, undershoot, or DC baseline restore that may be encountered in pulse applications. It is in fact, fundamentally capable of bipolar operation, and that is a question of appropriate power supply voltages. If used, for example with pairs of photodiodes receiving left and right hand polarized light, it could be fully bipolar.

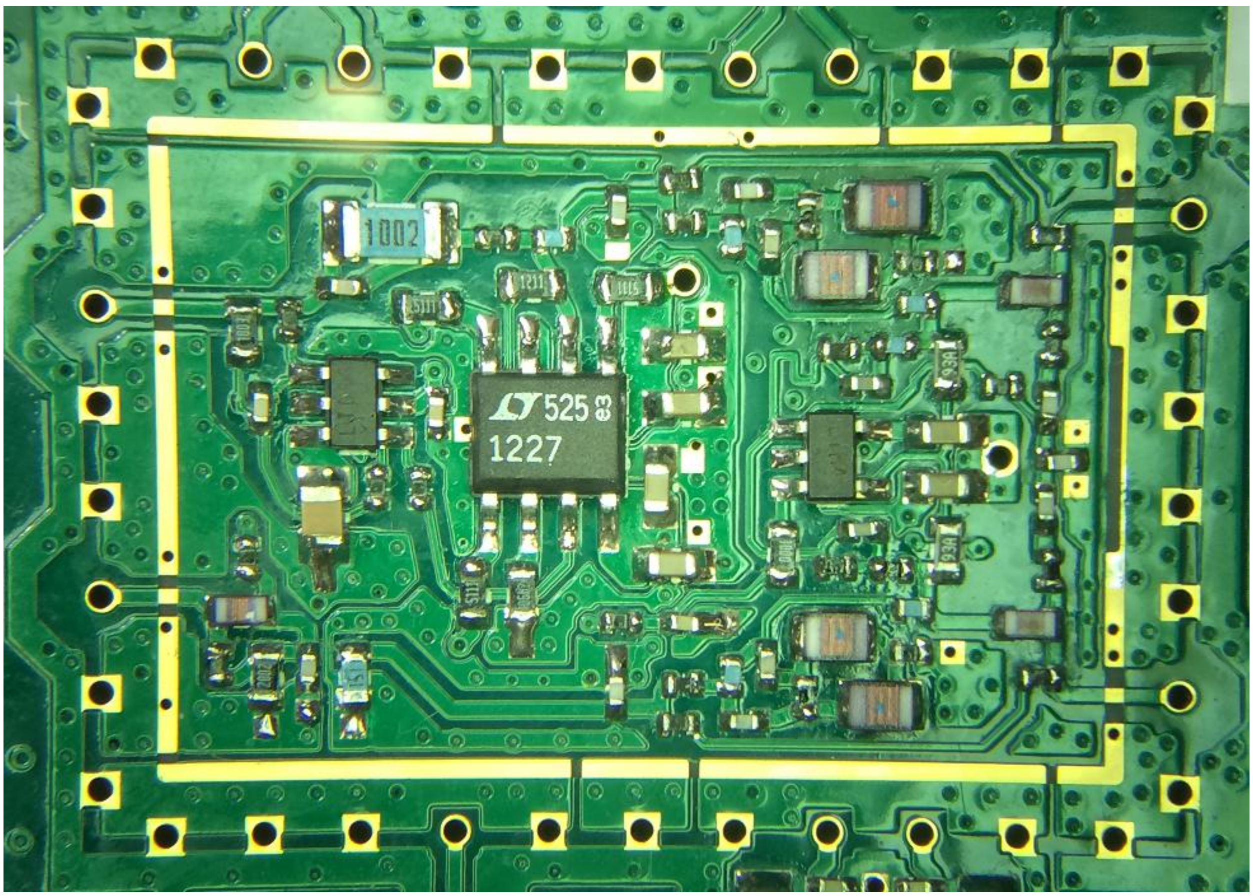


Figure 1 Prototype TIA/Driver   Devices from left to right LTC6268, LT1227, LT1395

The basic principle is that of using the highest trans-impedance gain possible, then attenuating into the ADC via the common mode servo, even though the ADC input range may already be quite large. In a TIA, the signal is proportional to the trans-impedance gain, whereas, the noise is proportional to the square root of the trans-impedance gain. Taken to extremes, using a second amplifier with high output excursion capability, SNR at high trans-impedance gain can be quite high. Glen Brisebois published an example of this involving a 50V supply, generating some controversy. The TIA itself is a composite amplifier composed of the LTC6268 500 MHz FET amplifier, followed by the LT1227, a 36V current feedback amplifier, which is used to develop the high signal swing, and the feedback. The LT1227 in fact, provides the signal power to drive the ADC. Taking this to ridiculous extremes in the form of yet higher voltage amplifiers may make sense for some applications.

The LTC6268 is a fast FET amplifier fabricated on a low voltage process, limited to 5V total supply, or in this first case, +3V, -2V. This would not be capable of developing enough swing to produce the high trans-impedance gain that would achieve the high dynamic range we want. The TIA gain could be regarded as being reduced by the common mode servo prior to the ADC, but keep in mind that both noise and signal are reduced, so the improvement in SNR is retained. The significant attenuation after the trans-impedance stage also reduces the contribution of the FET's voltage noise, its offset, and the 1/f region.

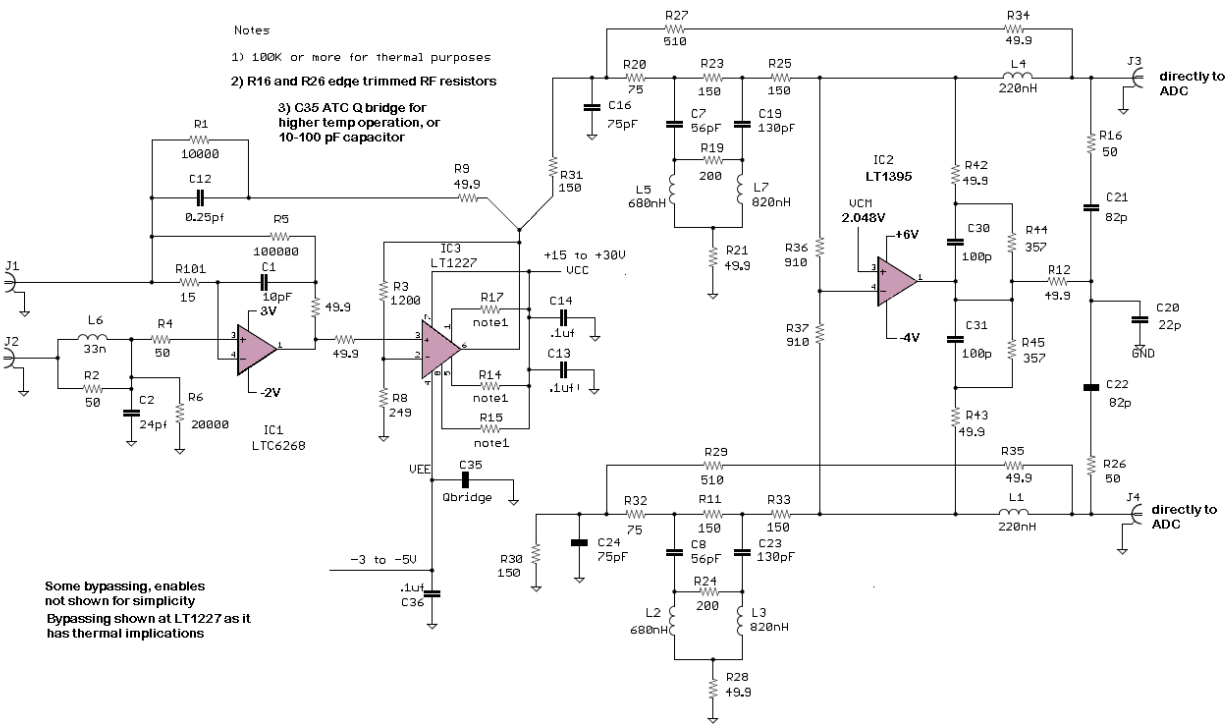


Figure 2 10K trans-impedance population of the board shown in figure 1

This circuit is shown there at 10K trans-impedance gain, In the TIA itself, intended for 1 mA diode current, with output excursion from the LT1227 at 0-10V. Some earlier FET amplifiers may be able to develop nearly this signal swing without needing the composite amplifier, or the complex power supply situation. This excursion is attenuated to 0-4V differential at the ADC. The single ended drive from the TIA is converted to differential drive for the ADC by what could be regarded as an electrical analogy of the Guanella balun.

At this trans-impedance gain, the second stage amplifier, an LTC1227 current feedback amplifier needs a positive rail of some 13-15V, with Vss at -3 to -5V. Higher supplies allow the LT1227 to develop 20-25V p-p, and higher trans-impedance gain can be achieved without much compromise to SNR or linearity. We have tested 40K, 100K and 200K trans-impedance gain, with corresponding changes to the attenuation between the TIA and the common mode servo.

At 10K trans-impedance gain with 1 mA diode current, these are high optical illumination levels, unless the diode area is very large. High diode capacitance will raise the noise floor, as noise gain is determined by $R_{Tiagain}/2*pi*f*C_{diode}$. High optical power may be encountered in interferometers.

As interferometers involve lasers, the noise of the laser would appear to be a limiting factor. In fact, this front end may be beneficial in measurement of laser noise levels. With the small active area of low capacitance diodes, the level of full scale illumination is higher than direct sunlight at the photodiode. This could be interpreted as suggesting that this can receive weak modulated signals in the presence of direct sunlight. The noise present in direct sunlight may have been expected to be a stumbling block, but in fact, the 80 KHz spurs present in the fluorescent light in our lab are worse by 50 dB, this is in absolute terms, not relative to the optical power. The entertainment value of this application has been high, as we can see, for example, that the 3 ballasts in the fixture above our bench are operating at slightly different frequencies. This is not electrical noise.

The LTC2387 has very high dynamic range, so this would be expected to be linear. A high degree of linearity in optical modulation however is not to be found. As a result we will focus on inter-modulation distortion. Linearity tests have been performed in several fashions. Two tone testing using a resistive combiner composed of 15K resistors (and 100K in the higher gain version) feeding the virtual ground at J1, a combiner composed of 2 x 15 pF capacitors, as well as an optical two tone test using two RED emitters, and one photodiode. All produce IM3/5 on the order of -110 to -115 dBfs, for two tones at *-13dBfs around 1 MHz. *(*equivalent to -7dBfs, but using ½ the input range) (with DC, or optical bias to +1/2fs)*

Both of the conventional signal source tests raise the noise gain, and as a result, also reduce feedback factor, potentially improving stability in the process, and possibly misleading. However, the combiner composed of two 15 pF capacitors is similar to the case with a 30 pF photodiode. As a result of past experience arguing the validity of test scenarios, we devised an optical two tone experiment, to emulate actual operating conditions. This used two modulated RED LEDs, Cree Xlamps, combined through free space at the photodiode. Using a Vishay TEMD5080X01 PIN photo diode, the IM3 was similar to levels seen in the direct injection of signal through high impedances.

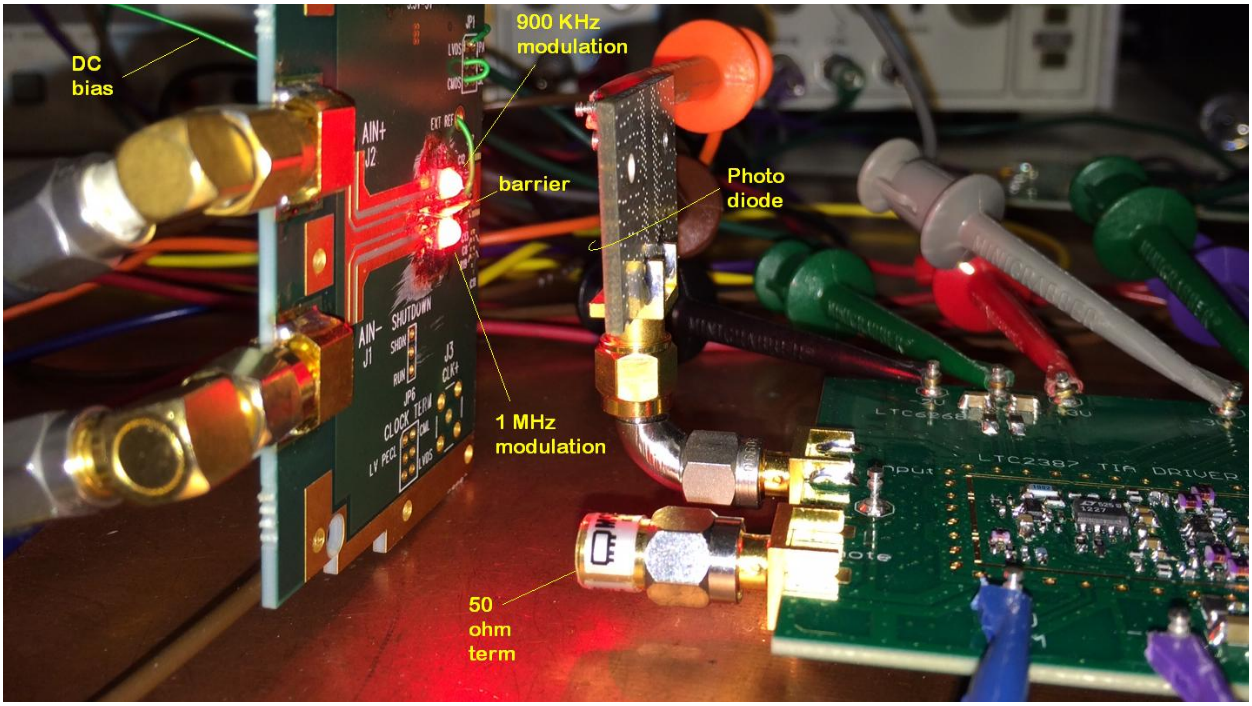


Figure 3 optical two tone experiment

There is evidence that the TIA itself is not dominant in this, as bias to the photodiode has some impact on IM products, as does sample rate, at least in the 200K version. The distortion is not reduced at lower frequency, also exonerating the amplifiers. The sensitivity to sample rate suggests that the returns from the output network are compromising the linearity of sampling somewhat, and there may be room for improvement in the output filter. Imbalance in the output network could potentially allow distortion in the common mode servo to be translated to differential form, but tests, balancing that network had little effect on the IM. Note that the simple harmonic distortion in the optical tests was very elevated, and we were focused only on odd order IM. Even order IM2 products were modest, but as these can be organized to fall out of band, if for example, this were used in free space optical communication, or sensing, with excitation using modulation BW limited to one octave. Tests with direct sequence spread spectrum waveforms suggest sensing using excitation involving this type of modulation may be practical.

These IM results with injection of signal through high impedance hint that this topology may be useful for sensing low amplitude signals riding on high voltage AC or DC, using very high value resistors, extending into Mega ohms.  How is this different than simply attenuating into a conventional differential amplifier you say?  If BW were limited to 20-30 KHz, the LTC6362 could produce similar results, at much lower power and complexity, but this composite TIA produces comparable SFDR to 2-3 MHz, 100 times the bandwidth of the LT6362.  This comes with no penalty in offset or the 1/f region, and the latter may be the deciding factor.

The offset performance of the circuit is largely dictated by the LTC6268 FET amplifier, if R5 is significantly higher in value than the trans-impedance gain setting resistor( R1) . Offset however is dominated by the LT1227 if there is too much local feedback around the LTC6268. The ADC is not a significant source of offset, even if the LTC6268 is equipped with no local DC feedback. The local feedback was added to ensure that, in the absence of power sequencing of the various supplies, the ADC is not overdriven. If DC offset is critical, there should be no local feedback (R5). If fast settling is more important than offset, there should be some local feedback around the FET stage.

Offset, distortion, and to a lesser extent noise, can be compromised by loose tolerance components in the signal paths through the common mode servo. The resistors in the output networks, at least R44 and R45, the most sensitive, should be 0.1%. If offset drift, in darkness, is of paramount importance, the virtual ground at the FET can be raised to 2.048V, (removing R6, rotating R30 to pick up bias on J2) in which case, there is no level shift involved in the common mode servo, only common mode AC suppression, and the tolerance of the resistors in the output network, to the right of the LTC1227, are dramatically less important. The FET then would operate on 0-5V. This has been tested in the 200K version, and offset, at a given sample rate, at room temperature does not vary more than 0.1 lsb. The filter used in the 10K version is quite absorptive from the perspective of the ADC, and in this case, offset does not vary much with sample rate. In the 200K version, offset is affected by sample rate. The filter in the 200K version provides more suppression in alias bands, where noise gain is high. This could be improved, time allowing, or with a board spin. To put this in perspective, 0.1lsb is 3 uV at the ADC. This is well within the ballpark of thermo-couple voltages. This topology, with significant attenuation after a composite TIA, not only reduces sensitivity to offset voltage in the TIA and 1/f noise in the FET, but also to thermocouple effects in the TIA. It does suggest that R30, and R31 should have been the same type of resistor. R30 was made larger to facilitate rework if it is rotated. Both should have been the same type. This level of sensitivity to offset also demands that the output network be completely replicated in differential form, out of concern for dissimilar metals in the two paths, from R31 and R30, through to the ADC. Extremely low offset drift, 1/f noise, and turbulent airflow over dissimilar metals, can be critical for resolving very short pulses… stretched.

Significantly higher trans-impedance gain, for lower current is also possible with loss of SNR. At modestly higher trans-impedance gain, If the trans-impedance gain at the amplifier were 40K for example, with 250uA photocurrent producing 25V, followed by an attenuation factor of 6 in the common mode servo, the noise density in the output of the driver would still be about 6 nV/rtHz , and would result in nearly the same SNR. Vcc must then be near 30V, and in fact, the gain in the LTC1227 stage must be higher, at approx (Vpeak/1.7). Very high trans-impedance gain may require the use of the LTC6268-10, compensated such that it is flat to some 50-60 MHz. Low trans-impedance gain is likely to be a bad idea with the -10 version. The high excursion at the output of the LT1227 seemingly would require the higher loop gain in the LTC6268-10 to maintain linearity. This requires very low value zero capacitors around R1. A version (shown below in marked up form) has been evaluated, and performs well, although, the use of the -10 version predictably requires customization of the compensation for each type of photo-diode. The zero cap around the -10 must be less than the diode capacitance by an order of magnitude, and more, because the main zero cap contributes to feedback factor. Note the 0.15pF at C12.

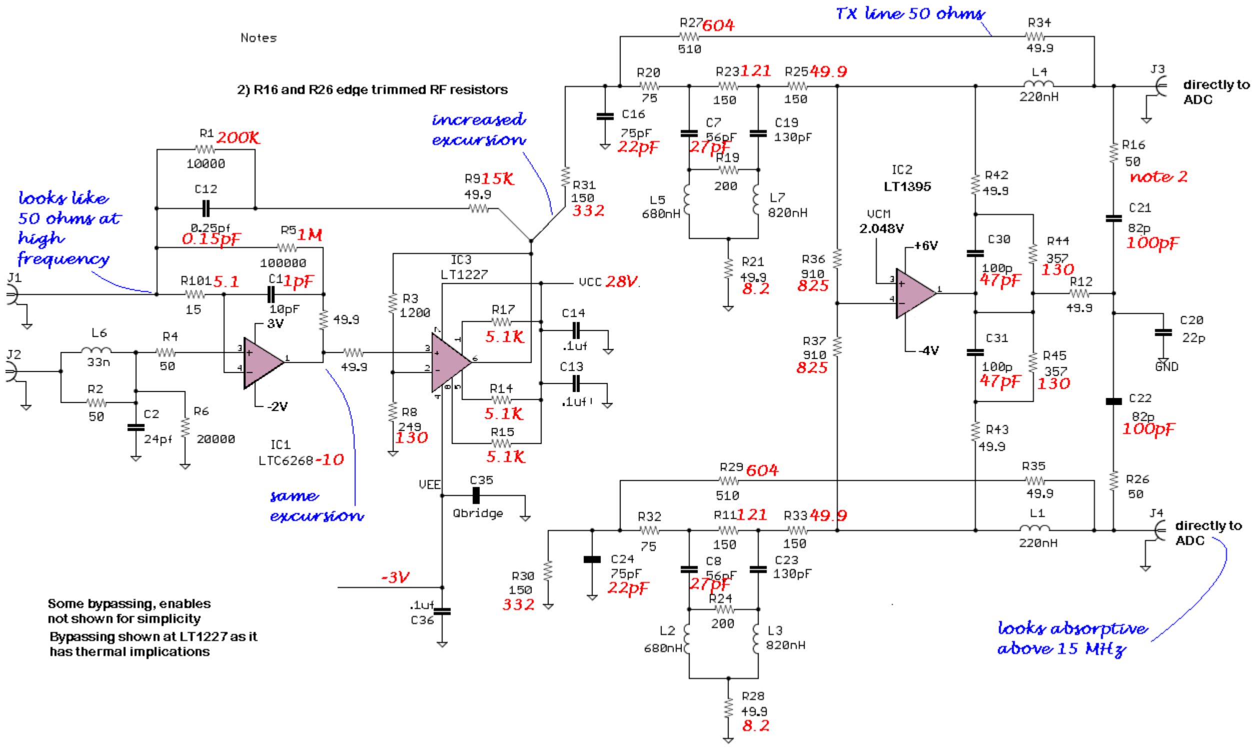


Figure 4 200K trans-impedance gain version

In the 10K case, the LTC1227 operates with a non-inverting gain of 5.8, limiting in the process, the output excursion required of the FET to approximately 1.7V. The limited output excursion from the FET requires that the LT1227 stage operate with higher gain in, for example, AV =10.2 in the 200K version. As the LTC1227 is within a control loop established by the LTC6268, the current feedback amplifier's noise and distortion contribution is reduced by the FET amplifier. In the 10K version, at 1 MHz, 90% of the feedback current comes from the LT1227. This suggests that its noise and distortion contribution will be reduced by 20 dB by the action of the FET amplifier. At 10 MHz and above, the LT1227 is only subject to local feedback, so its noise density would be high. In these respects, this design is similar to part I of this series. This then is where the filter will suppress the elevated noise region of the second stage amplifier at higher frequencies including the first alias bands and beyond. This filter is initially approximately Gaussian, and will act as a pulse stretching filter for fixed duration-unknown amplitude pulse applications, or fixed amplitude-unknown duration. Further into the stop band, the filter however has detuned elliptical like characteristics to suppress the first alias bands around 15 MHz. Transient response does not overshoot.

In the 10K version, the FET amplifier is configured essentially an integrator with 10 pF feedback capacitance, but as this is within a loop followed by gain of 5.8, its effective value is approximately 1.7 pF. This is in parallel with the 0.25pF zero cap in the global feedback path. As such, with 10K trans-impedance gain, the amplifier would have bandwidth of approximately 10 MHz, but is followed by a filter with a corner of approximately 2.5MHz. As this is a composite amplifier, the 10 pF zero capacitor

C1 around the LTC6268 is also the dominant pole.   The second amplifier must be fast in comparison, or rather, low delay, or it will compromise phase margin.

If, the LTC6268-10 were under consideration, C1, must be less than 10% of the diode capacitance.  The other zero capacitor, C14, will also affect loop stability, and must be a small fraction of 1 pF for most trans-impedance gains.   For sensors with less than 10 pF, the LTC6268-10 arguably would be impractical, unless input capacitance is added.  As shown in the 10K version, this is stable with anywhere from open on the SMA (but with board trace capacitance) to 100 pF, and perhaps beyond. It is stable with diode capacitance at the end of a transmission line, or even an open stub.  With the LTC6268-10, a source termination resistor at the diode may be required for stability, depending on cable length. This does not affect noise density appreciably. Some photodiodes may not require this, depending on internal series resistance.

The second stage LT1227 current feedback amplifier was chosen for the combination of high slew rate and 36V supplies.  Noise, is not as important as it is within the loop controlled by the FET amplifier, at least within the BW defined by the low-pass filter.  Other high slew amplifiers operating on higher supply voltages may allow similar SNR at higher trans-impedance gain.

The LTC6268, does have a relatively high 1/f corner.  However, In this implementation, at 10K trans-impedance gain in the TIA, followed by 8 dB attenuation into the ADC, and as the ADC dominates the wideband noise floor, it results in a 1/f corner at about 1 KHz. In a higher gain version, with 200K trans-impedance gain, and 15 dB attenuation into the ADC, requiring +25V supply for the LT1227, the noise is dominated by the 200K impedance, and noise folding.  In this case, the 1/f corner is pushed down further, in theory to about 50 Hz, but I have not been able to validate this.  A long term average of a large transform does not show it, and observing offset variation has been inconclusive.  This article will be updated when it can be determined.

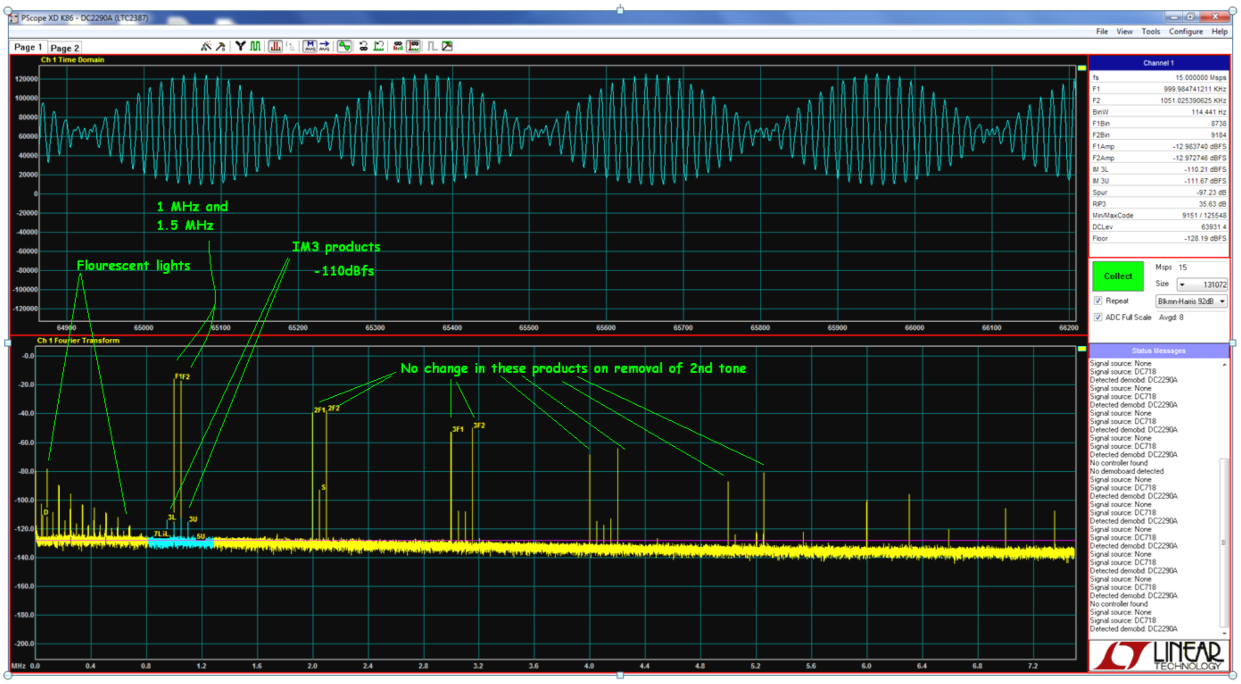


Figure 5 optical two tone in 40K version

The plot in figure 5 is the inter-modulation test results from the experiment in figure 3, combining two modulated optical signals in one photodiode. The only important information in these plots is the level of 3L and 3U at -110 and -111 dBfs.  The simple harmonics of these two signals do not change in any discernable way when either is turned off.

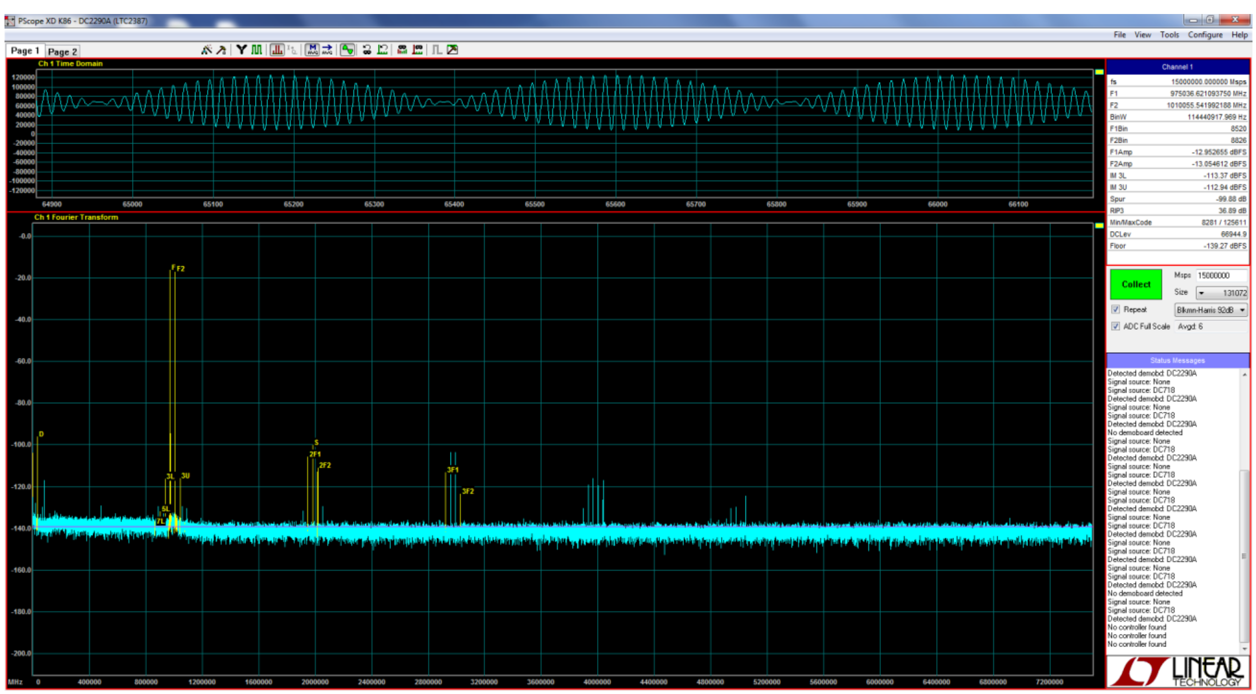

Figure  6, Electrical two tone test using two 15K resistors as a combiner (10K version)

There are other candidate amplifiers from within LTC's portfolio that may be suitable. The LTC6253 is available in the SOT23 package, and although not a FET amplifier, does have fairly low noise current, and voltage. Other potentially interesting alternatives from LTC are not compatible with the SOT23 footprint on this board. The LTC6244 could be used in this topology. It does have a very low 1/f corner for an amplifier with 1 pA input current. It does require quite different compensation, and output filtering, and even then, would require DSP suppression of frequencies above 1 MHz. However, with the filter topology on this board, the alias bands can be adequately suppressed. Other filter populations may be of interest, with the LTC6268-10/LT1227 composite as, although the Guassian filter has 2.5 MHz BW, the TIA can be compensated to remain flat to 10 MHz.

Extending the frequency response to 10 MHz will result in some loss of SNR, and the common mode servo is best below a few MHz, as is the LTC2387, and it may be better to entertain this topology with the LTC2270 or even higher speed ADCs.

These boards can be provided, bare, partially populated, or customized if warranted.