Design Considerations for the Analog Front End of a Pulse Oximeter

Matthew Hann
Senior Applications Engineer
Texas Instruments, Tucson
hann_matthew@ti.com

Pulse oximetry is a technique used to measure the oxygen saturation in blood and other vital signs such as ECG and pulse rate. Aside from its obvious clinical uses, pulse oximetry has been implemented in various applications such as neo-natal care and the monitoring of jet pilot consciousness at high altitudes. Pulse oximeters range from portable to industrial grade, the best of which require a unique marriage of high performance analog and smart digital filtering. This presentation will cover the design considerations of the analog front end which includes the photodiode sensor, sensor conditioning devices and techniques, basic analog filtering and sampling, and the LED driver for the pulse circuit for both portable and industrial grade applications.

Scope of Presentation

- Survey General Analog Techniques/Circuits Used in Pulse-Oximetry
- Survey General Analog Content Used in Pulse-Oximetry
- Confine Analog Investigation to Single Supply Domain ONLY
- ***NOT*** Detailed Reference Design

Pulse Oximetry is not like ECG in its strategy; it is a very broad topic. This presentation could be 1000 slides long and only graze the surface of what could be covered. For this reason, this presentation is limited in its scope and depth. It will give a very general overview of SOME (definitely not all) techniques and TI devices that might be a good fit for pulse ox applications. Since single supply design in general can be more difficult than dual supply, this presentation will focus on analog circuits designed for single supply applications.

What is Pulse Oximetry?

- The “Pulse” in Pulse Oximetry refers to the pulsatile nature of blood
- Aims at providing accurate correlation between an empirical measurement, S_pO_2, and the true arterial O_2 saturation, S_aO_2

Basic Pulse Oximetry Model
Assumptions

- Hemoglobin is the Dominant Light Absorber
- Oxygenated Hemoglobin (HbO_2) and Deoxygenated Hemoglobin (Hb) have different absorptive (extinction) coefficients
- Extinction Coefficients Differ Linearly with Wavelength
- ONLY HbO_2 and Hb Present in Blood
- Overall S_aO_2 calculation is a quotient from wavelength measurements
- Light Scattering Allows Sufficient Illumination
- Normal Reading for S_aO_2 % = 95%

Applications for Pulse Oximetry

- Standard Monitoring for ICU
- Standard Monitoring for Surgery
- Anesthesia Monitoring
- Direct Organ Monitoring
- Tissue Transfer and Limb Fracture Setting
- Dental Pulp Blood Supply and Viability
- Neonatal Monitoring
- Monitoring for High Altitudes (Pilots)
- Exercise Monitoring
- Sleep Studies
- Stress Testing

Topics to Be Covered

- ✓Biochemistry Background for Pulse Oximetry
- ✓Beer's Law: Empirical Understanding
- ✓Block Diagram for Pulse Oximetry
- ✓Pulse Sequence for LED
- ✓LED Circuit Design
- ✓LED Power Considerations
- ✓LED Peak Wavelength Shift Compensation
- ✓Photodiodes and Transimpedance Amplifiers
- ✓Improving Noise Rejection in Pulse-Ox Front Ends
- ✓Improving Dynamic Range in Pulse-Ox Systems
- ✓Choosing the ADC in Pulse-Ox Systems

✓Biochemistry Background for Pulse Oximetry

✓Beer's Law: Empirical Understanding

✓Block Diagram for Pulse Oximetry

✓Pulse Sequence for LED

✓LED Circuit Design

✓LED Power Considerations

✓LED Peak Wavelength Shift Compensation

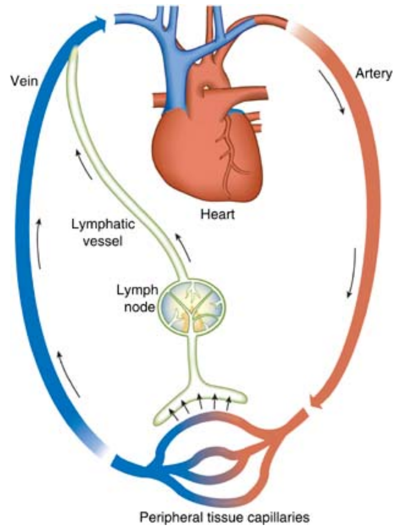
✓Photodiodes and Transimpedance Amplifiers

✓Improving Noise Rejection in Pulse-Ox Front Ends

✓Improving Dynamic Range in Pulse-Ox Systems

✓Choosing the ADC in Pulse-Ox Systems

Human Vascular System Relevant Terms



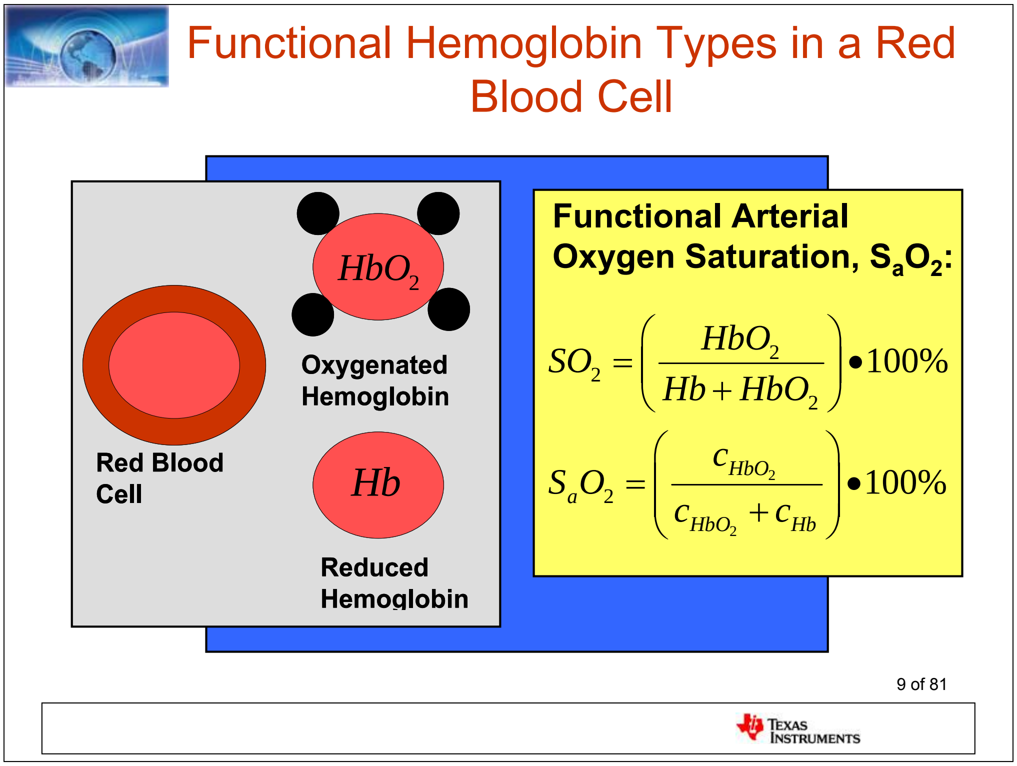
<u>Artery:</u> Carries Oxygenated Blood from Heart to Body

<u>Vein:</u> Carries De-Oxygenated Blood back to Heart

<u>Systole:</u> Contraction Phase of Heart Cycle

<u>Diastole:</u> Relaxation Phase of Heart Cycle

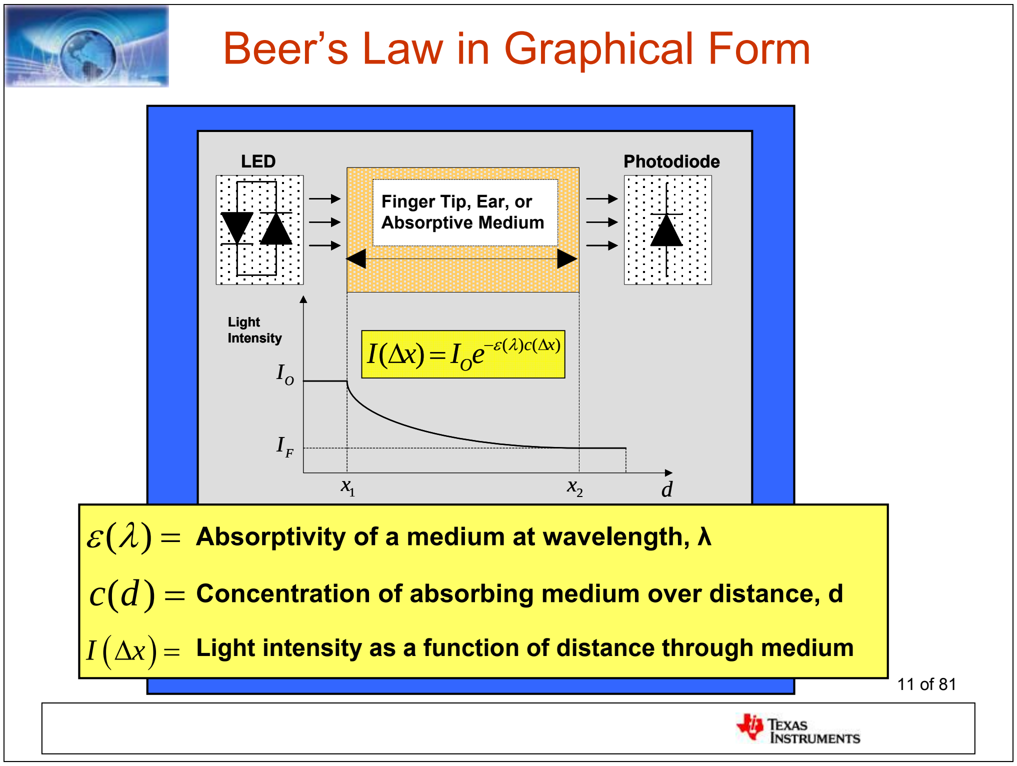
The “pulse” that will be analyzed in Pulse Ox is an artifact of the contraction of the heart during systole and diastole. Pulse Ox systems are designed to monitor arteries because these are the oxygen-carrying vessels in the body. Residing within the arteries is a molecule called hemoglobin which binds with oxygen so that it may be carried to different parts of the body for use.



Hemoglobin is the molecule in blood that binds to oxygen and carries it to the necessary parts of the body. Most hemoglobins in healthy individuals are functional. These are the hemoglobins that are either bound to oxygen or capable of being bound to oxygen; therefore, they are the ones of primary concern in pulse oximetry. Hemoglobins that are considered “dsyfunctional” are methemoglobin, carboxyhemoglobin, sulfhemoglobin, and carboxysulfhemoglobin.

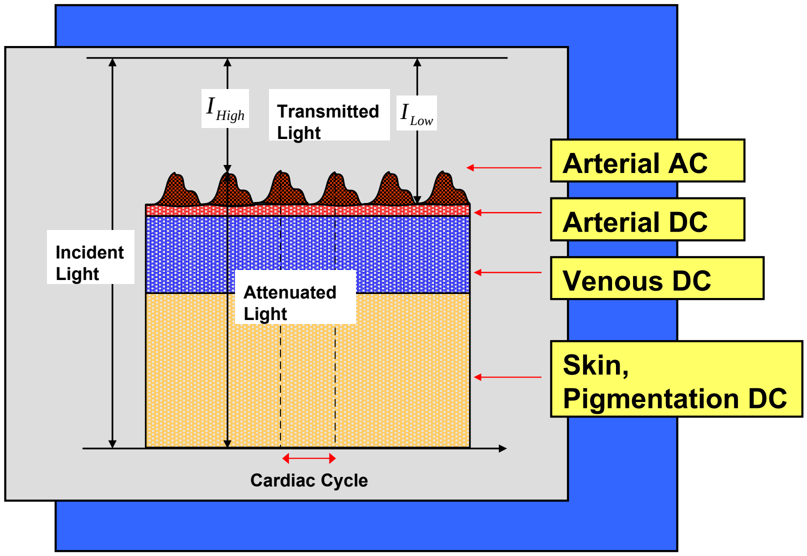
The importance of oxygenated vs. reduced hemoglobin is that it gives a mathematical relationship for calculating the oxygen concentration in the blood. This is commonly referred to as “oxygen saturation,” or SaO2.

- ✓Biochemistry Background for Pulse Oximetry
- ✓**Beer's Law: Empirical Understanding**
- ✓Block Diagram for Pulse Oximetry
- ✓Pulse Sequence for LED
- ✓LED Circuit Design
- ✓LED Power Considerations
- ✓LED Peak Wavelength Shift Compensation
- ✓Photodiodes and Transimpedance Amplifiers
- ✓Improving Noise Rejection in Pulse-Ox Front Ends
- ✓Improving Dynamic Range in Pulse-Ox Systems
- ✓Choosing the ADC in Pulse-Ox Systems



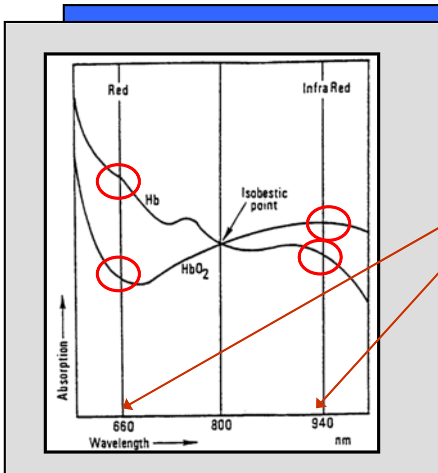
Light traveling through a medium is either absorbed, transmitted, or reflected. In the case of a finger pulse oximeter, the main absorbers are the pigments in the skin, bones, venous blood, and non-pulsing arterial blood. According to Beer's law, given a constant absorptive medium the optical transmission will be attenuated by the product of the extinction coefficient of the medium and the distance of the medium. The angle of incidence will modulate the optical transmission.

Multiple Mediums, Attenuation Due to Blood and Skin



This is another look at the DC components of tissue attenuation vs. the time-varying arterial components. This diagram shows that most of the DC attenuation is due to the skin and its pigmentation, the veins, and the arterial DC which is the non time-varying portion of the artery which happens during the resting phase of the heart (diastole).

Extinction Coefficients of Hb and HbO_2



- 660nm and 940nm (R and IR)
- ↑ and ↓ λ = steep absorption curve
- Large difference in $\varepsilon(\lambda_R)$ and $\varepsilon(\lambda_{IR})$

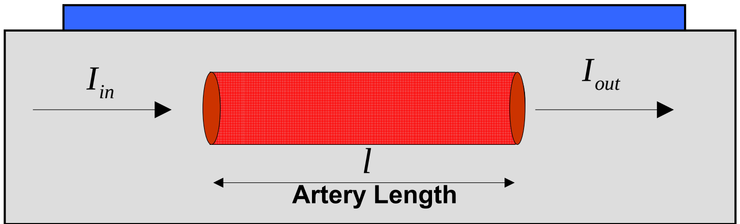
Absorbance is proportional to

$$A = -\ln T = \varepsilon(\lambda)c(d)$$

Total Absorption proportional to Extinction Coefficient (λ) * Concentration of Medium

The differences in attenuation due to oxygenated and deoxygenated hemoglobin are due in large part to the difference in extinction coefficients at different wavelengths. The large difference in extinction coefficients at 660nm and 940nm allow the differentiation of Hb and HbO2 for the SaO2 calculation. The total absorption is proportional to the extinction coefficient e (wavelength) multiplied by the concentration. Again, the operative assumption is that the light source will be absorbed primarily by these 2 types of hemoglobin.

Derivation of S_aO_2



$$I_{out_{\lambda R}} = I_{in_{\lambda R}} \bullet 10^{-\left(\alpha_{o1} \bullet C_{HbO_2} + \alpha_{r1} \bullet C_{Hb}\right) \bullet l}$$

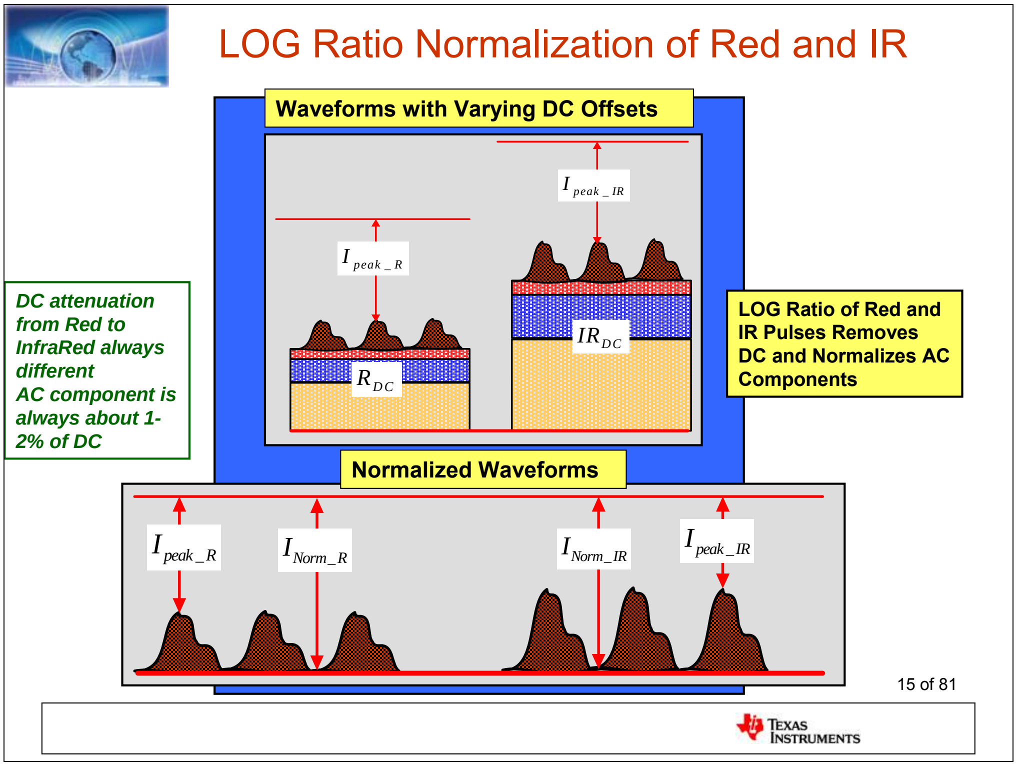
$$I_{out_{\lambda IR}} = I_{in_{\lambda IR}} \bullet 10^{-\left(\alpha_{o2} \bullet C_{HbO_2} + \alpha_{r2} \bullet C_{Hb}\right) \bullet l}$$

$$R = \frac{\log_{10}\left(I_{out_{\lambda R}} / I_{in_{\lambda R}}\right)}{\log_{10}\left(I_{out_{\lambda IR}} / I_{in_{\lambda IR}}\right)}$$

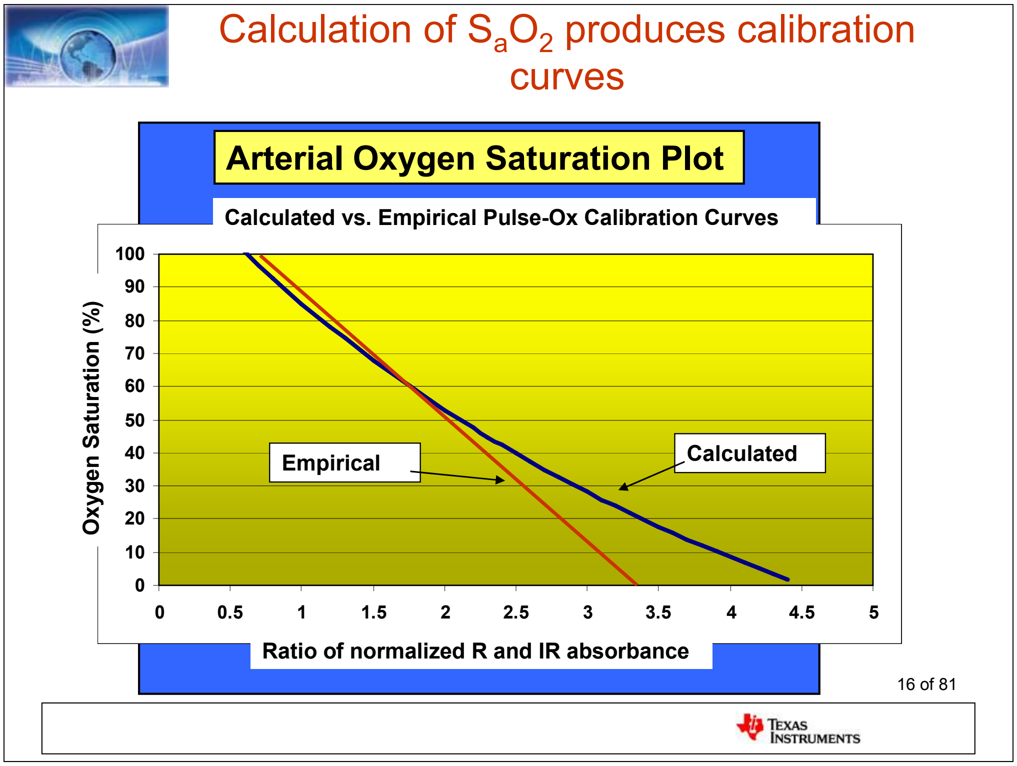
$$S_aO_2 = \frac{C_{HbO_2}}{C_{HbO_2} + C_{Hb}} = \frac{\alpha_{r2} \bullet R - \alpha_{r1}}{\left(\alpha_{r2} - \alpha_{o2}\right) \bullet R - \left(\alpha_{r1} - \alpha_{o1}\right)}$$

Output Light Intensity (I_{out}) proportional to Input Light Intensity (I_{in})
Absorption for Hb and HbO_2 varies with λ
and is proportional to emissivity constant (α) * concentration (C)

In this derivation, the length of the artery remains constant; the output light intensity, Iout, is proportional to the input light intensity Iin. The absorption for Hb and HbO2 varies with wavelength and is proportional to the emissivity constant times the concentration.



The absorbance of light is A=-ln(Transmittance) = -ln(E(lambda)*C(d)). Since the DC attenuation from Red to InfraRed will always be different and the AC component is always 1-2% of DC, it makes sense that we would only want to compare the time-varying signal components of these 2 wavelengths. The beauty of the natural log is that by creating ratio of the absorbances, the DC component of distance for both RED and InfraRed drops out of the equation. This leaves us only with the change in distance (AC amplitude) of Red and InfraRed. This is the signal that we will try to create with a good LED pulse and condition with good analog circuitry.



The calculated SaO2 using Beer's Law assumes NO SCATTERING of light or REFLECTION with respect to the receiving medium, which is simply not the case. Some light is scattered and some light is reflected. This accounts for part of the difference between the empirical and the calculated results shown in the graph. A secondary effect is the difference in the optical medium between systole (contraction) and diastole (relaxation) of the artery. During this time the optical medium acts like a lens and can create different a different reflection.

In spite of these shortcomings, the pulse oximeter is still accurate enough for clinical use.

✓Biochemistry Background for Pulse Oximetry

✓Beer's Law: Empirical Understanding

✓Block Diagram for Pulse Oximetry

✓Pulse Sequence for LED

✓LED Circuit Design

✓LED Power Considerations

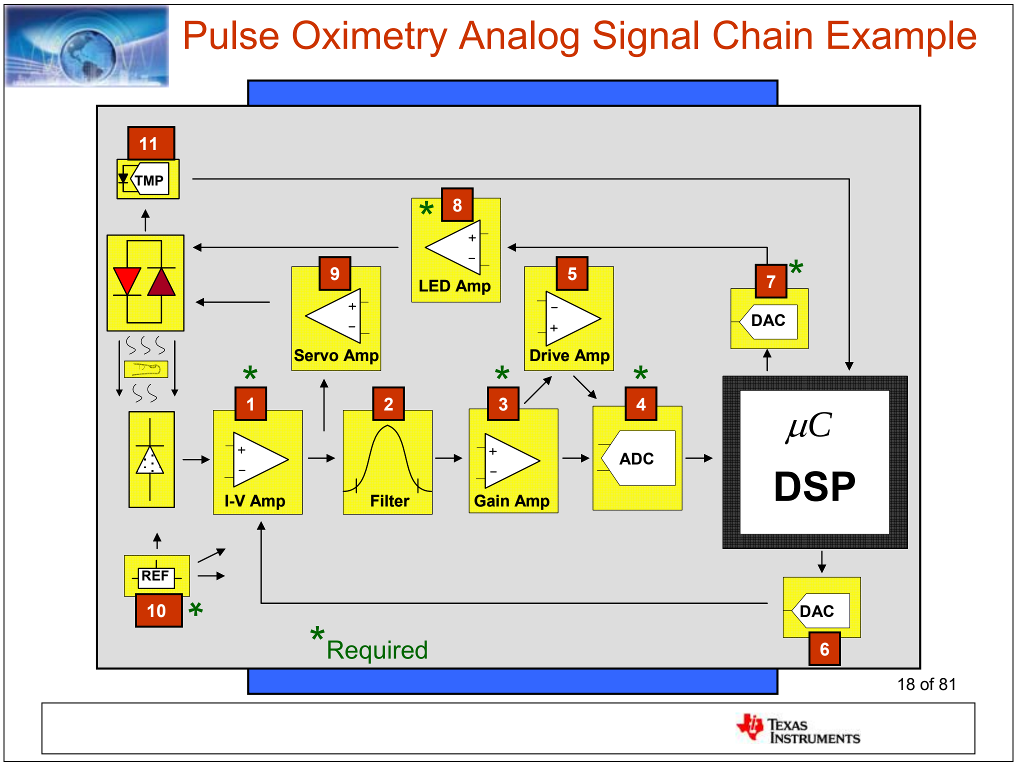
✓LED Peak Wavelength Shift Compensation

✓Photodiodes and Transimpedance Amplifiers

✓Improving Noise Rejection in Pulse-Ox Front Ends

✓Improving Dynamic Range in Pulse-Ox Systems

✓Choosing the ADC in Pulse-Ox Systems



This block diagram shows most of the potential locations that analog can be used in a pulse oximeter. Some components are optional depending on whether the pulse oximeter is for clinical or portable use. Also, some of the analog functions shown might be accomplished with digital processing in the DSP. Whether it makes sense to perform a specific function such as DC filtering and/or feedback in the analog or digital domain is an application-dependent choice.

(1) I-V conversion of the photodiode output—REQUIRED

(2) Analog Notch filter—OPTIONAL, can be done in DSP as well

(3) AC gain amplifier—REQUIRED

(4) A/D Converter—REQUIRED

(5) A/D Drive Amplifier—OPTIONAL, output gain stage may be sufficient bandwidth for settling

(6) DAC for DC offsetting—OPTIONAL, feedback to LED for light intensity may be enough to auto-adjust range

(7) DAC to Control Drive Amplifier for LED: REQUIRED

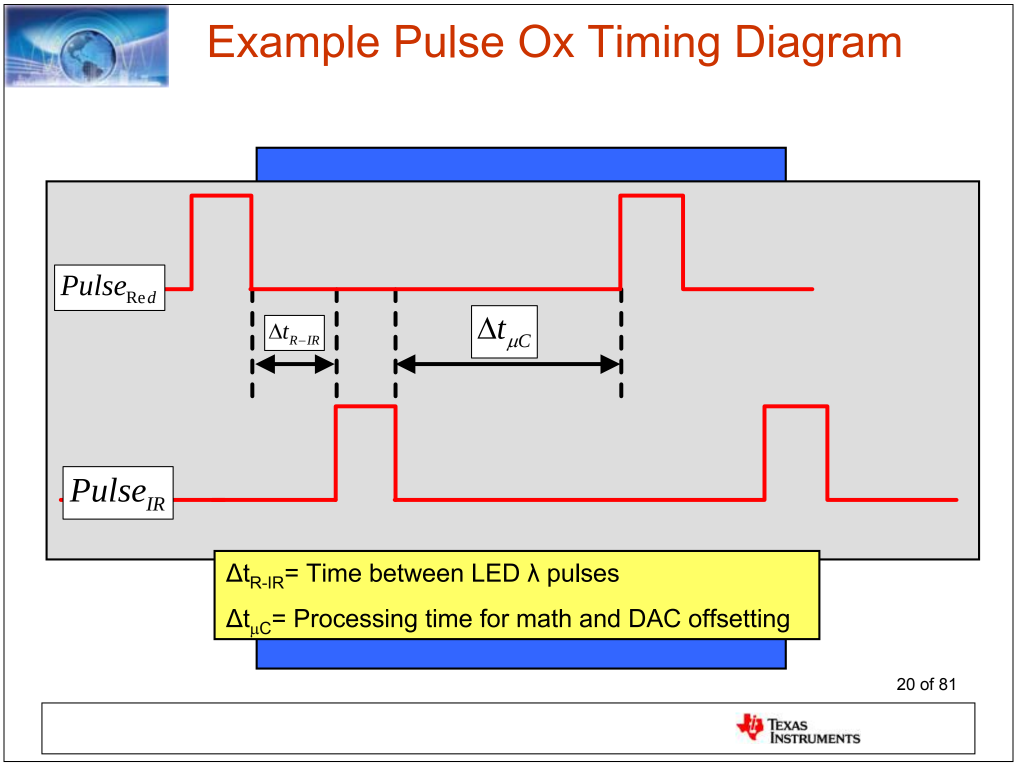
(8) Drive Amplifier to LED: REQUIRED

(9) Analog feedback Amplifier for LED intensity control: OPTIONAL, may not be needed in lower end pulse oximeters

(10) Analog Voltage Reference for A/D, DAC: REQUIRED

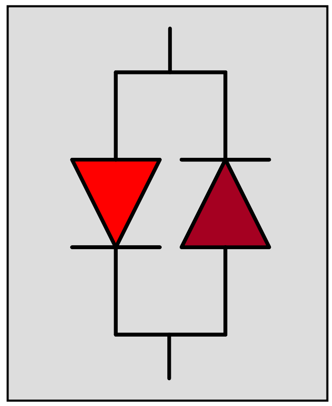
(11) LED Temperature Sensor: OPTIONAL, this is for LED wavelength shifting due to temperature compensation. May be done in other ways or may not be necessary in lower end portable oximeters

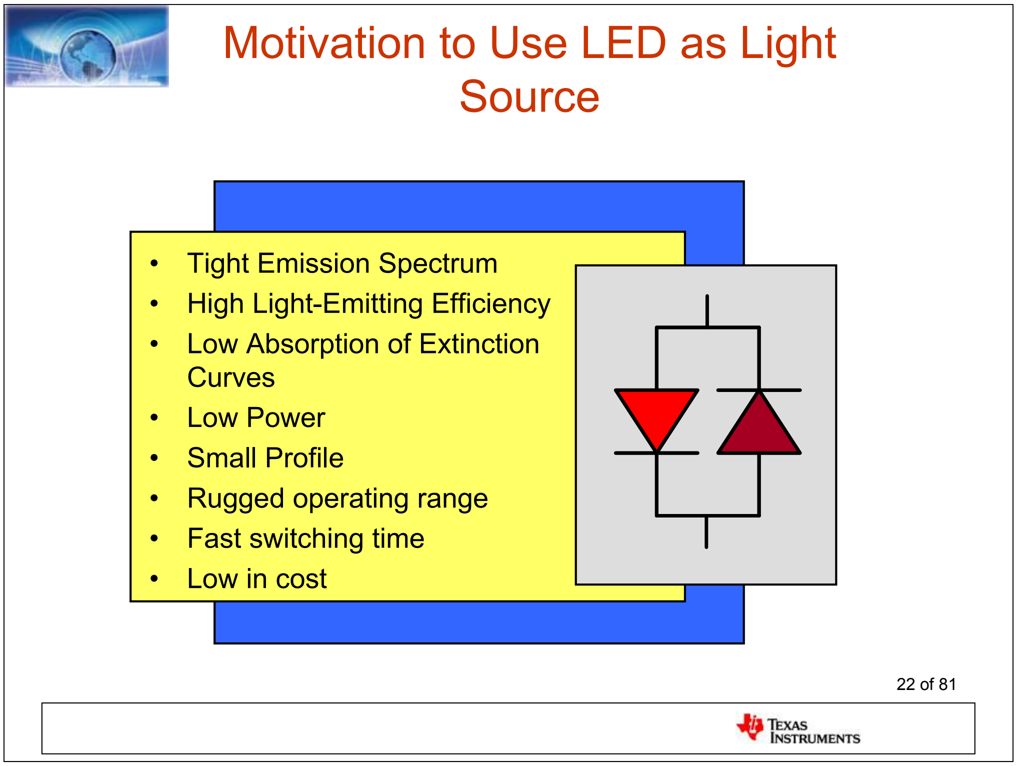
- ✓Biochemistry Background for Pulse Oximetry
- ✓Beer's Law: Empirical Understanding
- ✓Block Diagram for Pulse Oximetry
- ✓**Pulse Sequence for LED**
- ✓LED Circuit Design
- ✓LED Power Considerations
- ✓LED Peak Wavelength Shift Compensation
- ✓Photodiodes and Transimpedance Amplifiers
- ✓Improving Noise Rejection in Pulse-Ox Front Ends
- ✓Improving Dynamic Range in Pulse-Ox Systems
- ✓Choosing the ADC in Pulse-Ox Systems



This is a typical example of the pulse timing diagram using an LED driver. The pulse between the red and the infrared must be sufficient to differentiate the two and there must be sufficient processing time to take the measurement. How many different pulse cycles are needed for an accurate measurement is application dependent.

Design of the LED Driver for a Pulse Oximeter





The following are the reasons for choosing an LED as the light source as opposed to another type of light source:

Tight Emission Spectrum Targets Specific Wavelengths at 660 and 940nm

Low Absorption of oxyhemoglobin extinction curves corresponds to LED wavelength availability

Radiated power and size are low compared to other light-emitting source options

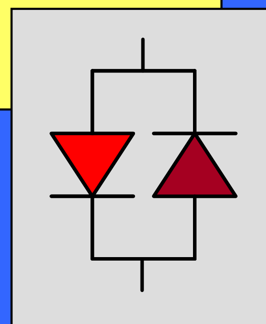
Very rugged with operating range of -40C to 125C

Very fast switching time

Low in cost; may be purchased in bulk for disposable probes.

Design Considerations of the LED Driver

- Bandwidth
- Common Mode/Saturation Range
- Output Swing vs. Output Current
- Slew Rate
- Supply Range
- Power Dissipation



LED’s themselves have ns rise times and are fast enough to produce peak power for any application; however, a composite LED driver must be able to follow a given pulse edge in a consistent manner to give a consistent reading. Especially for the case of single supply drivers with DAC feedback or light feedback, it is important to make sure that the min and max inputs never exceed the common mode range of an amplifier or the threshold/saturation of a transistor driver. There are many different ways to create an effective LED driver. This presentation will focus constructing LED drivers around OPA circuits, recruiting the use of transistors in the cases where high power is needed. In each design shown there will be a main set resistor across which a differential or single-ended voltage is applied to yield the desired current. Peak power and duty cycle must be considered as this will affect the overall junction temperature which will cause an inherent shift of the AC/DC characteristics of the amplifier.

✓Biochemistry Background for Pulse Oximetry

✓Beer's Law: Empirical Understanding

✓Block Diagram for Pulse Oximetry

✓Pulse Sequence for LED

✓**LED Circuit Design**

✓LED Power Considerations

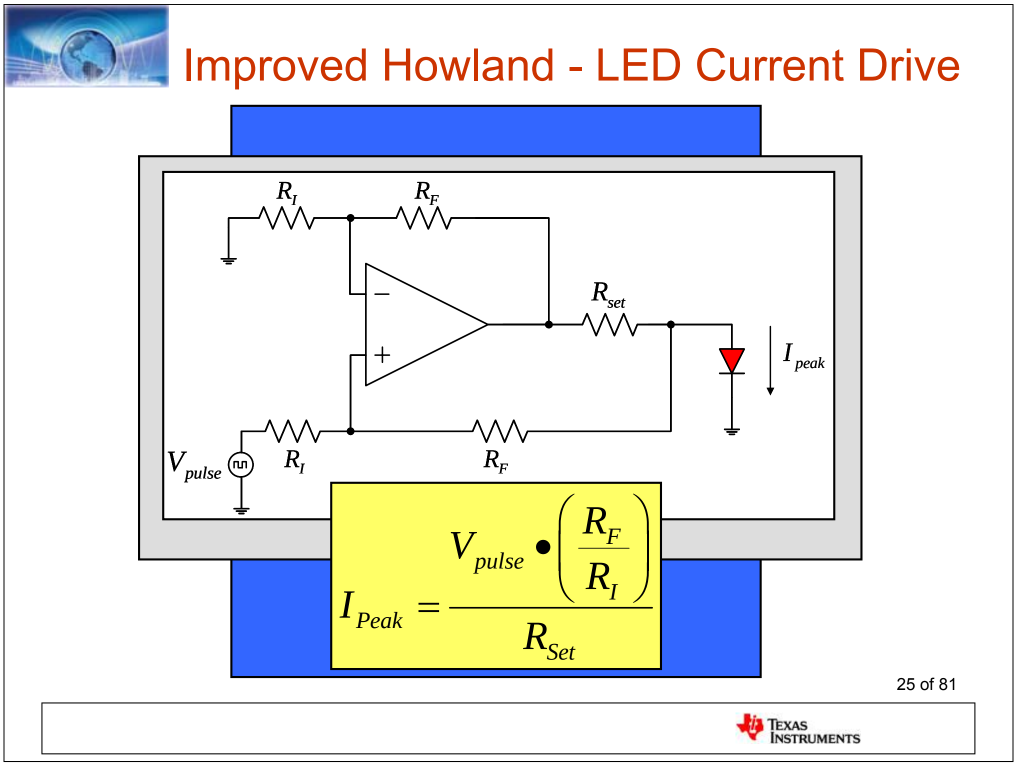
✓LED Peak Wavelength Shift Compensation

✓Photodiodes and Transimpedance Amplifiers

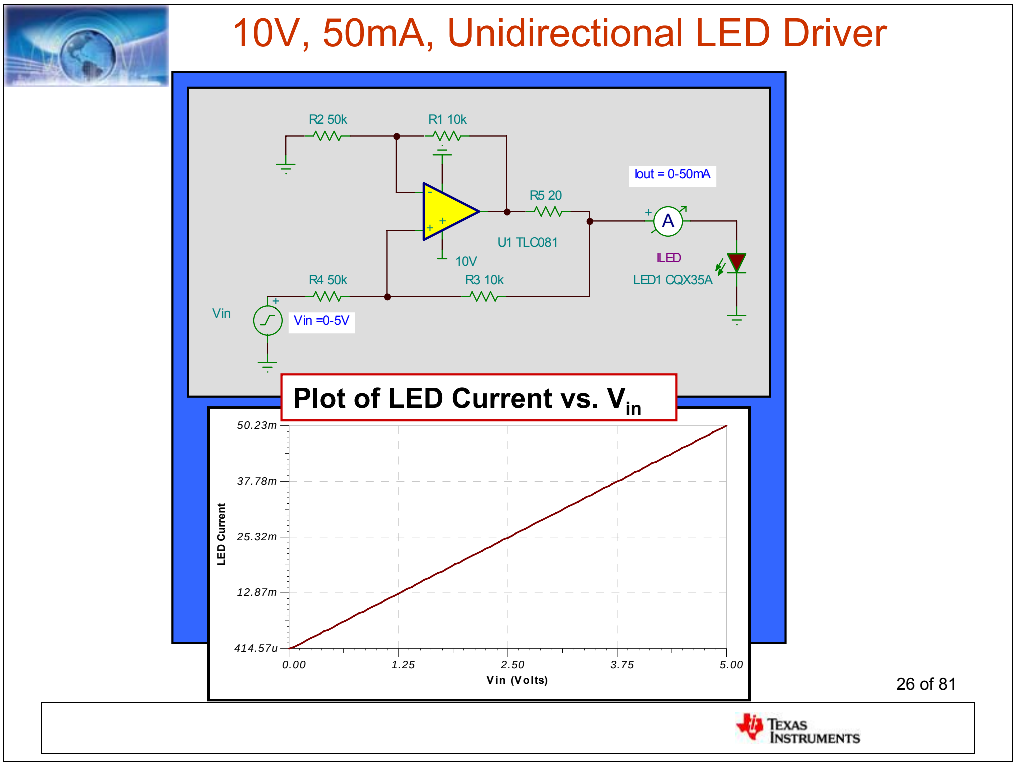
✓Improving Noise Rejection in Pulse-Ox Front Ends

✓Improving Dynamic Range in Pulse-Ox Systems

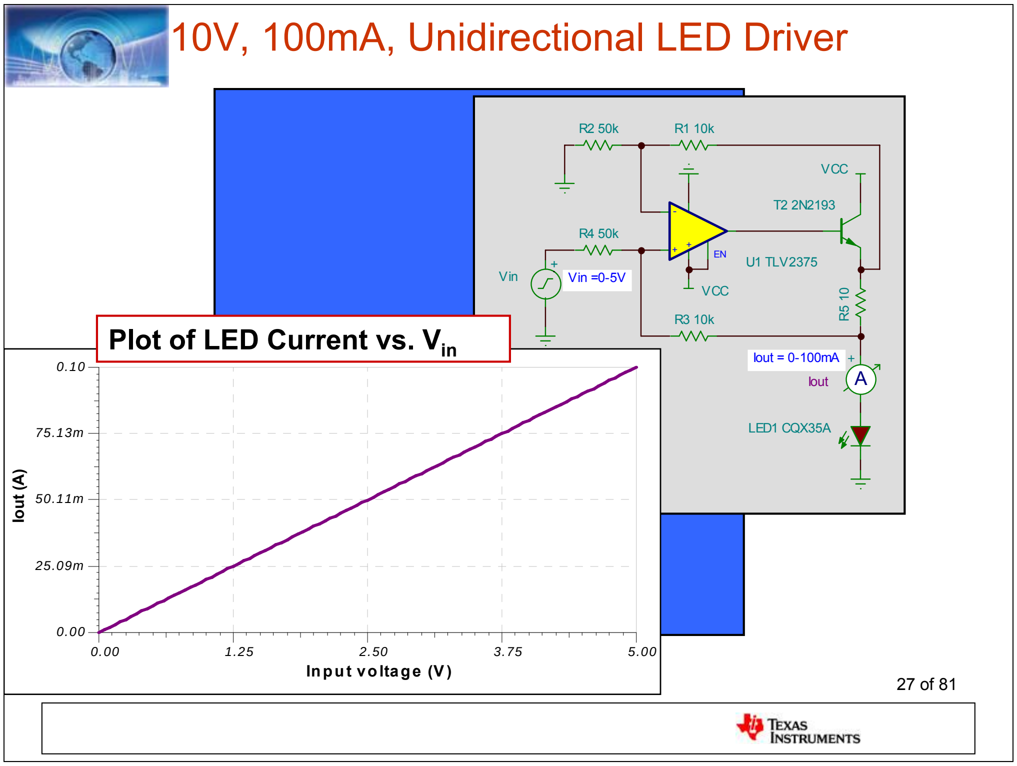
✓Choosing the ADC in Pulse-Ox Systems



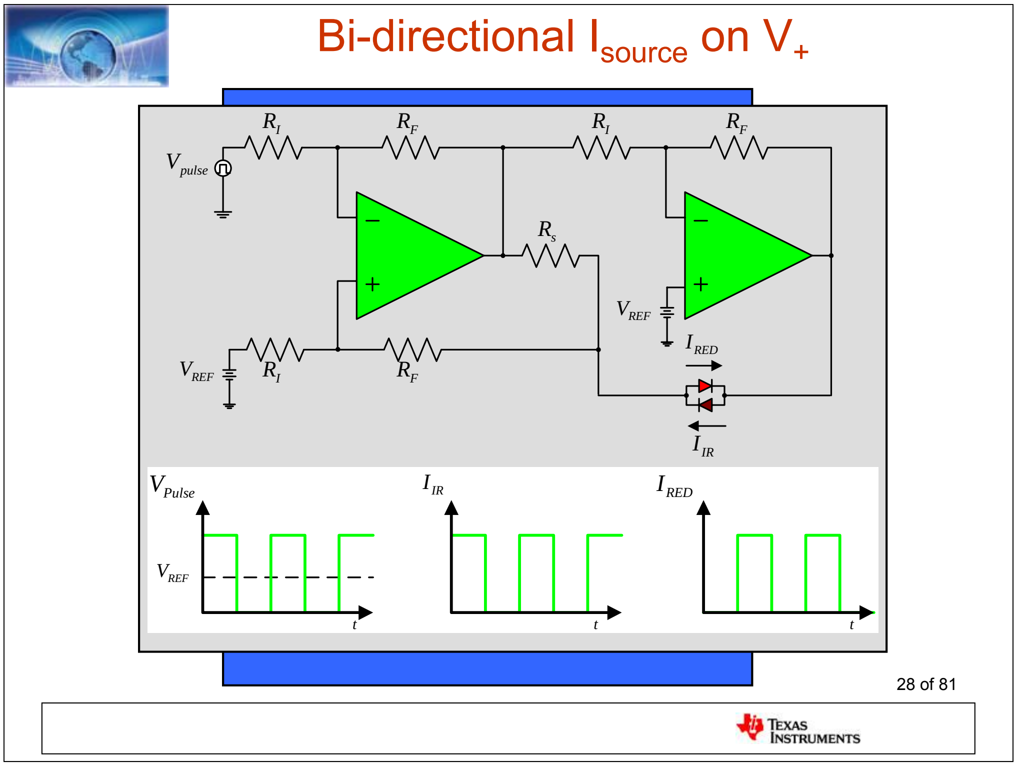
There are many ways to create an effective LED current source for pulse oximetry. This presentation will focus on a current source topology referred to as the "Improved Howland." The Improved Howland configuration for an OPA is a very common, cheap way to create a current source. In fact, all of the LED current sources in this presentation are versions of the Howland. With .1% resistors it is possible to achieve 1% current accuracy at the output. The feedback resistors are scaled such that the input never exceeds the common mode range of the inputs of the OPA and the output swing/ output current limitations of the OPA. The set resistor linearly modulates the current and can be tweaked to help the output swing and to minimize power dissipation. This particular configuration is good for unidirectional control through the excitation diode. A unidirectional driver may be desirable over a bidirectional driver if different current excitation levels are needed for different LED wavelengths. Also, if higher than 20mA is desired (which is the case for most OPA's) a higher power (and more costly) OPA will need to be implemented OR an output transistor power boost.



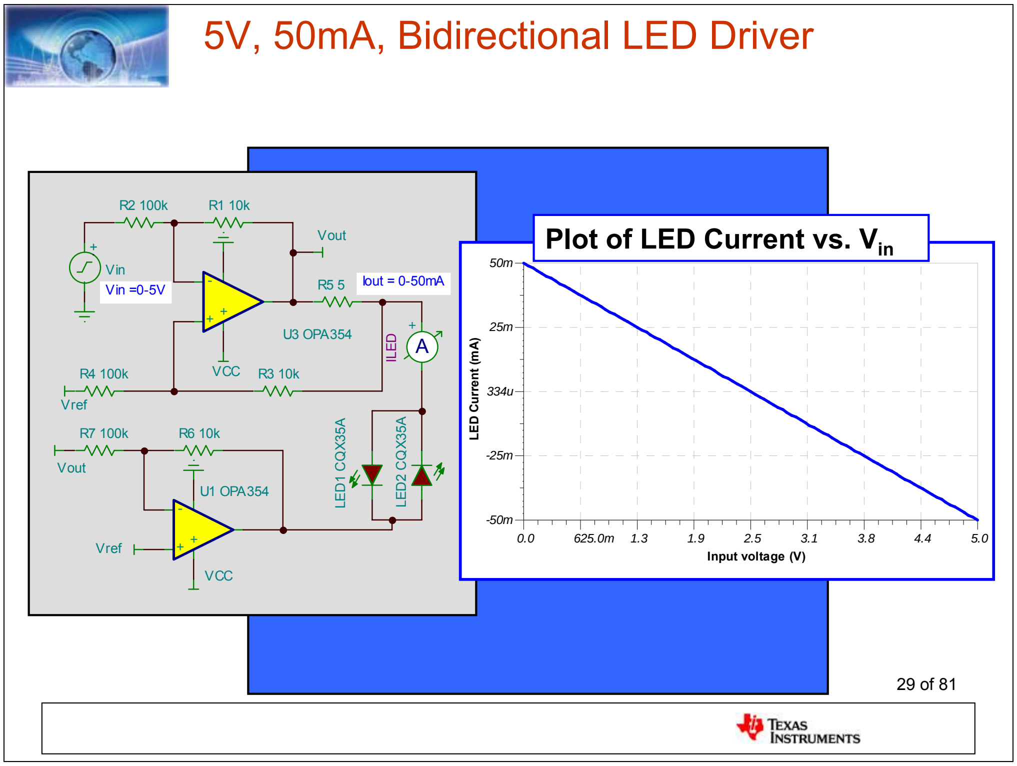
This LED Driver relies on the output current capability of the drive amplifier. It is difficult to find an amplifier that fits the bill of > 5V supply that can source and sink around 50mA without going to an expensive power amplifier which will be very high profile and expensive for what is needed. The TLC081-083 amplifiers come in a PowerPAD package which allows better power dissipation. If source/sink on a single 10V supply is needed, the TLC081 can be bridged with another to provide source/sink capabilities. This technique will be shown.



If higher than 50mA current is necessary, adding an output transistor will allow power boosting for the output current. Because the current will be driven by the transistor, any cheap OPA that fits the supply specification will work. The scaling of the resistors will depend on the desired output current, the common mode input range of the amplifier, and the output swing limitations of the amplifier.

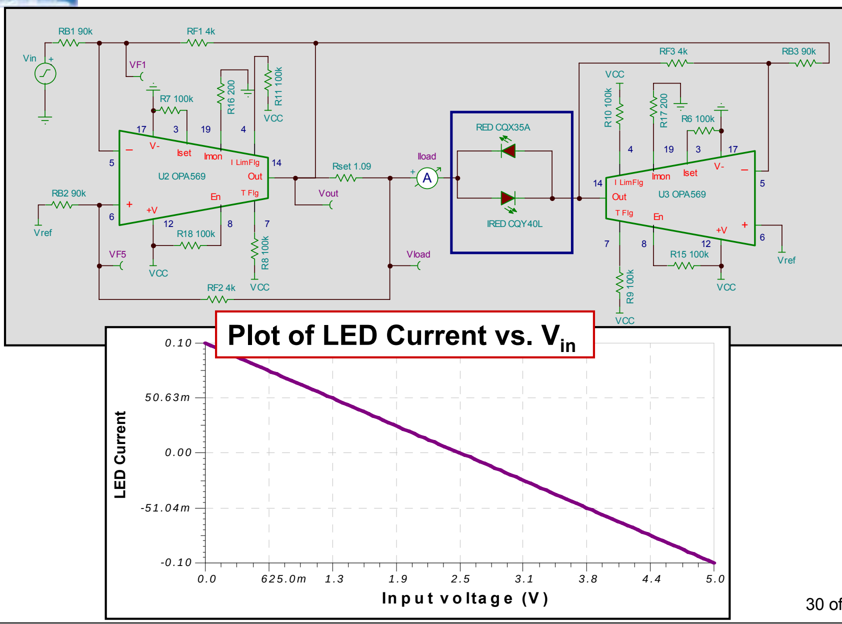


With a single supply pulse source the LED is sourcing or sinking current depending on the phase of the pulse, Vpulse. With the LED's configured as shown the IR turns on during the sourcing phase and the R turns on during the sinking phase. The waveforms for the current are separated to show this.



For the single supply bidirectional current drive case, 2 OPA's can be "bridged" to achieve the desired source/sink current. The current can be boosted even more by adding a transistor at the output of each amplifier, or by using the circuit on the next slide.

5V, 2A, Bidirectional LED Driver



This circuit uses either the OPA567 or OPA569 in a bridged Howland configuration. These devices represent the “coup de gras” when it comes to output current drive and swing to the rail. When soldered down to a thermal land, these devices can source and sink 2A of current with no problems. It is doubtful that 2A of current will ever be utilized as any one LED may not require more than 100mA of peak current; however, the power is available if needed.

✓Biochemistry Background for Pulse Oximetry

✓Beer's Law: Empirical Understanding

✓Block Diagram for Pulse Oximetry

✓Pulse Sequence for LED

✓LED Circuit Design

✓**LED Power Considerations**

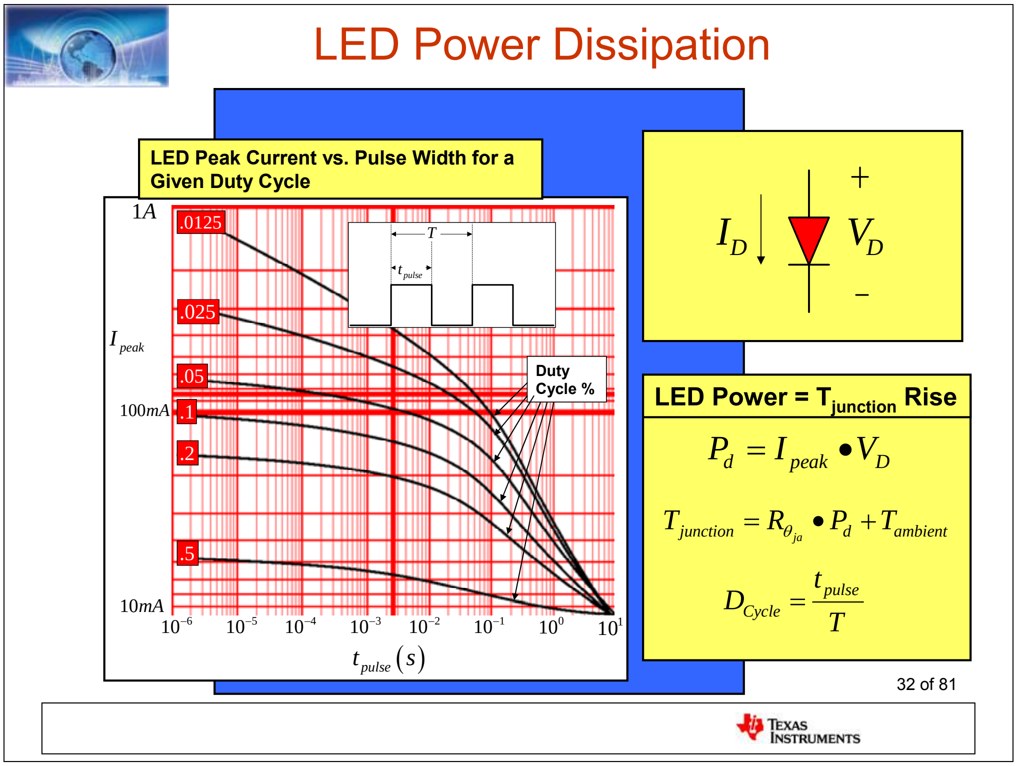
✓LED Peak Wavelength Shift Compensation

✓Photodiodes and Transimpedance Amplifiers

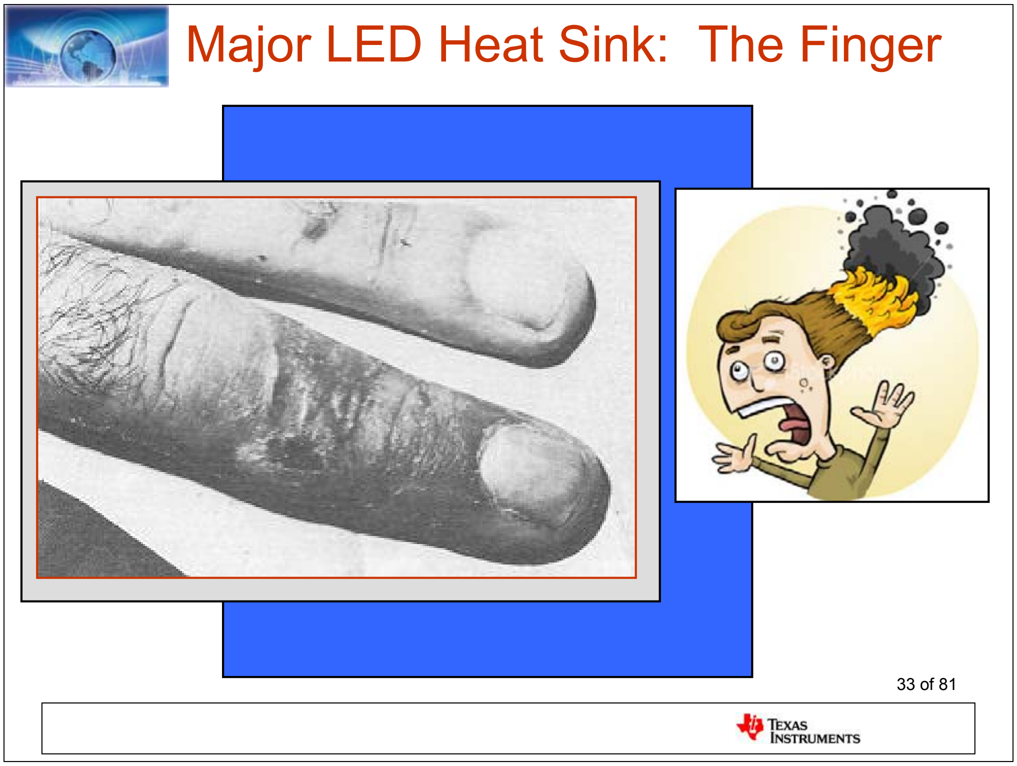
✓Improving Noise Rejection in Pulse-Ox Front Ends

✓Improving Dynamic Range in Pulse-Ox Systems

✓Choosing the ADC in Pulse-Ox Systems



The frequency of an LED driver is application-dependent. Some higher speed applications require the pulse frequency to be higher than others where the duty cycle can be as high as 25%. Portable applications oftentimes require lower power devices which in general may not have the bandwidth to settle within a fast pulse. In such instances it is important to pay attention to the duty cycle as the pulse rate will modulate the effective theta-ja of the diode which ultimately affects the junction temperature. A shift in junction temperature will cause a shift in peak wavelength; a shift in peak wavelength will cause error in the SP02 reading if not properly addressed with temperature compensation. Ultimately, the designer must choose a duty cycle that meets the system needs from the standpoint of bandwidth, 50-60Hz noise sampling, and power dissipation.



LED temperature must not get out of hand—here is a case where prolonged exposure to a hot LED causes burns on the skin.

✓Biochemistry Background for Pulse Oximetry

✓Beer's Law: Empirical Understanding

✓Block Diagram for Pulse Oximetry

✓Pulse Sequence for LED

✓LED Circuit Design

✓LED Power Considerations

✓LED Peak Wavelength Shift Compensation

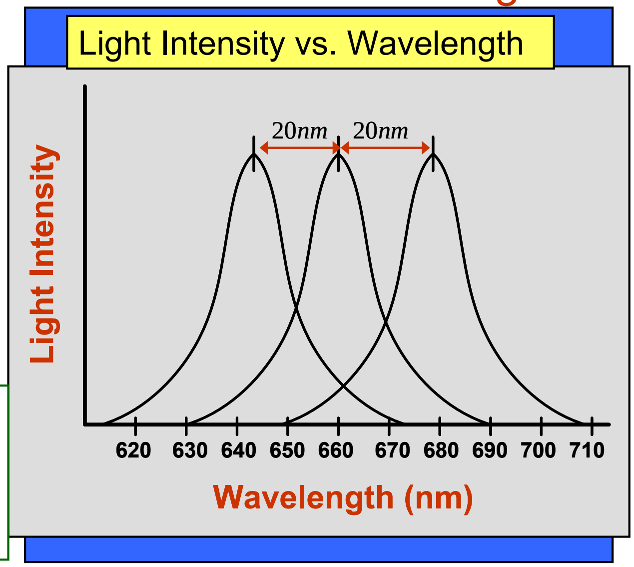
✓Photodiodes and Transimpedance Amplifiers

✓Improving Noise Rejection in Pulse-Ox Front Ends

✓Improving Dynamic Range in Pulse-Ox Systems

✓Choosing the ADC in Pulse-Ox Systems

LED Challenge: Overcoming Shifts in Peak Wavelength

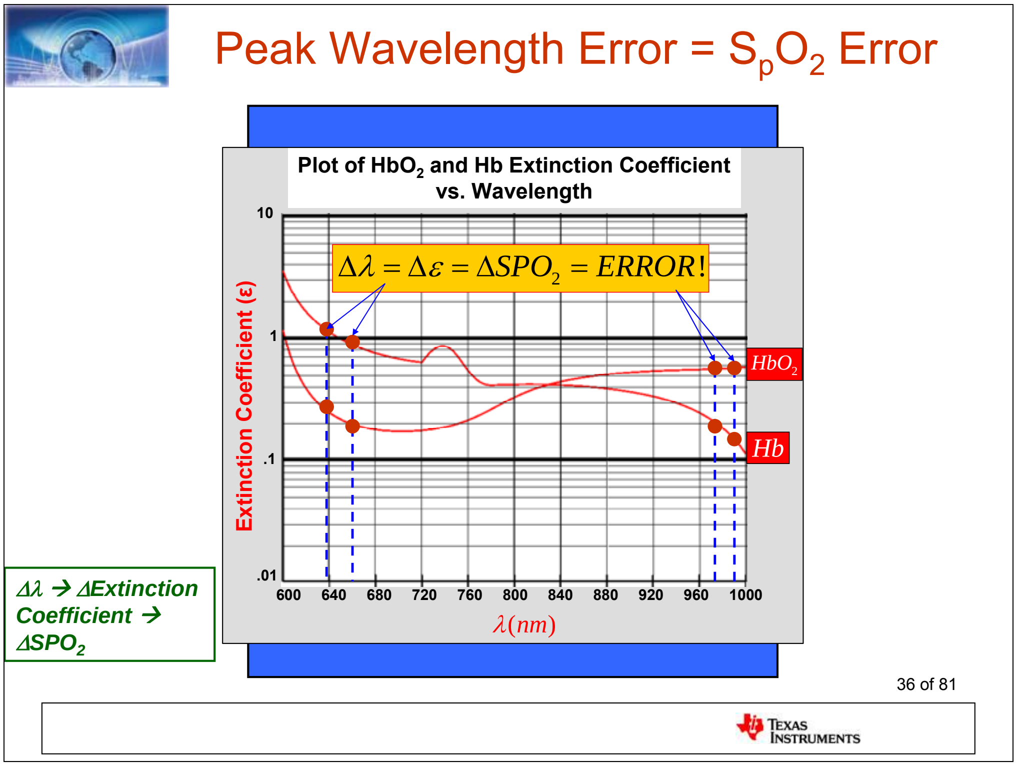


LED λ can vary by 1-5% initial accuracy
LED can drift with temperature

35 of 81

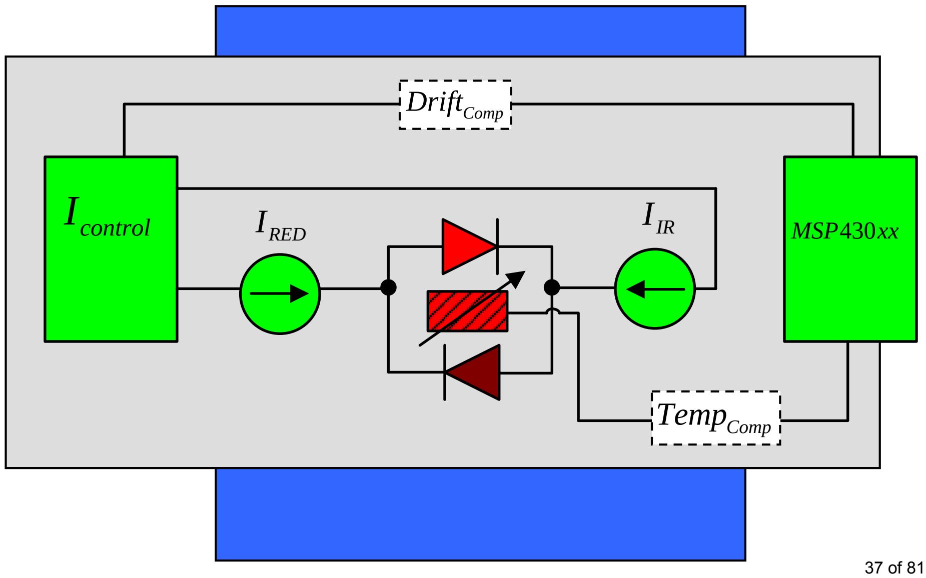
Texas Instruments

LED’s are chosen for their tight control over peak wavelength; however, there are 2 issues that must be overcome: (1) The “out-of-box” wavelength can vary 1-5% and must be measured such that an accurate calculation can be made. Likewise, LED’s can drift with temperature. Temperature compensation is a must in high accuracy pulse-ox systems.



As was shown earlier, the oxygen saturation, SP02, is calculated based on the extinction coefficient at a specific wavelength for oxygenated hemoglobin (Hb02) and reduced hemoglobin. If this wavelength shifts, so too will the extinction coefficient. This means the SPO2 reading will be off and could possibly be so far off that it wouldn't be able to properly register a catastrophic depletion of O2 which would be very bad. How bad? See the next slides…

LED Peak Wavelength Shift Compensation



Texas Instruments

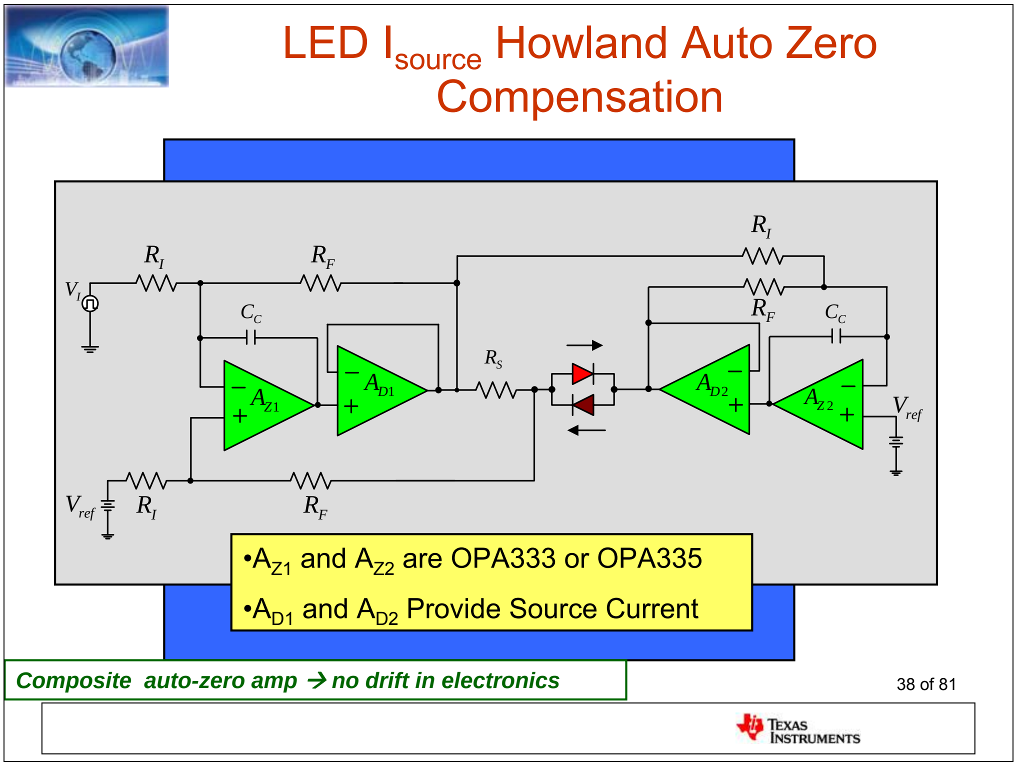
Peak λ Result of Temperature Drift

Problem 1: Drift in Component Offsets

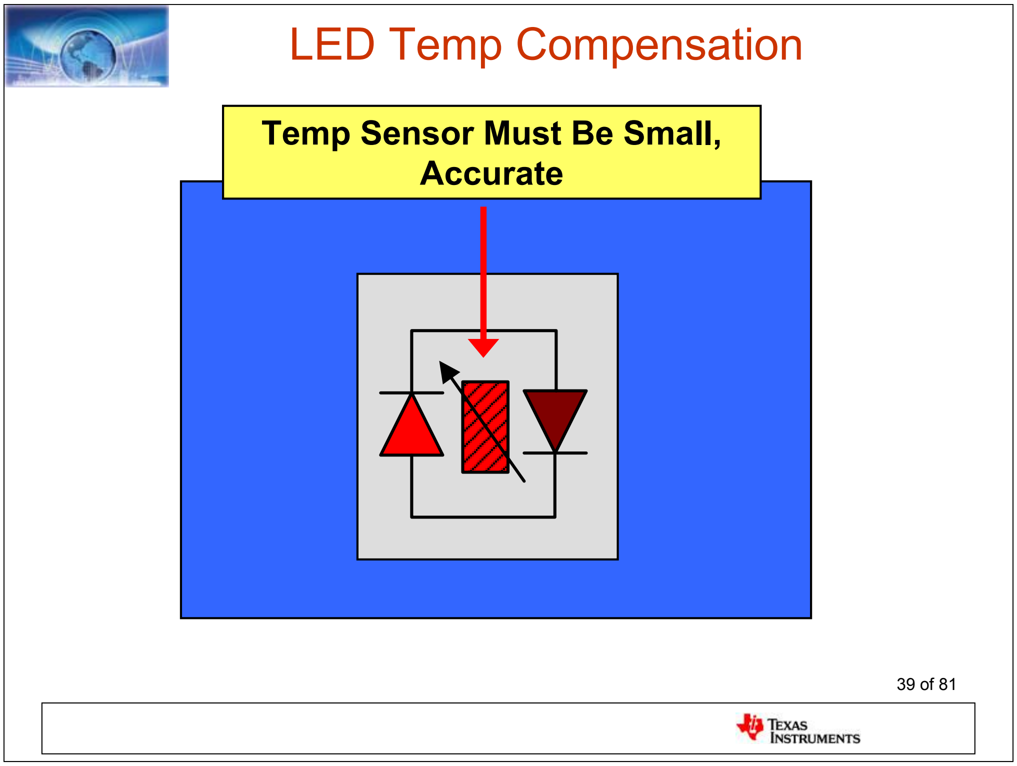
Answer: Compensate in Analog or Software

Problem 2: Shift in Forward Voltage of LED

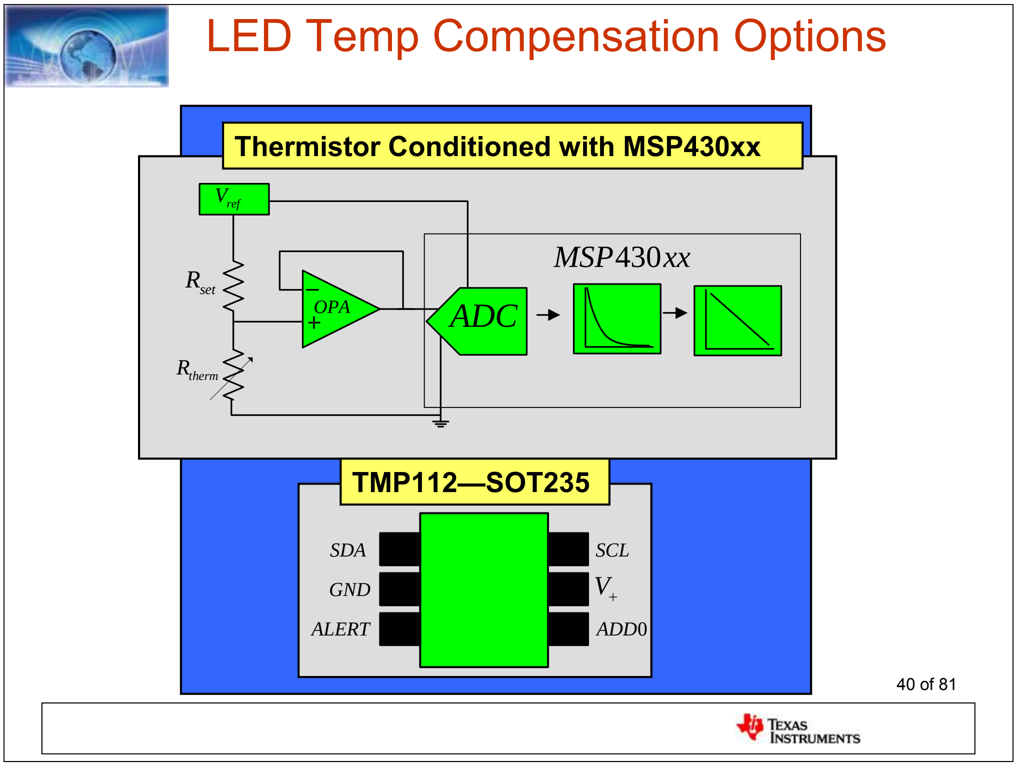
Answer: Know Power and Temperature; Compensate in Software



Putting an auto zero amplifier in front of the drive amplifier helps with DC offset drift; however, the challenge that one may encounter with this application is the slew rate limit of the front end auto zero when using this approach. This general topology can be tailored to the specific application. Perhaps a good compromise in this case is to use a shunt resistor that is small enough not to drift and monitor temperature at the same time with an non auto-zeroed amplifier.



The temperature sensing element needs to be located very close to the anode and cathode of both the Red and IR LED, almost as if it was manufactured as part of the device. Consequently, a very small temperature sensing element is required



The choice between conditioning using a thermistor will depend on the accuracy needed, the availability of conditioning circuitry, lookup table, etc. The TMP112 will provide a pure digital output temperature to .5C.

✓Biochemistry Background for Pulse Oximetry

✓Beer's Law: Empirical Understanding

✓Block Diagram for Pulse Oximetry

✓Pulse Sequence for LED

✓LED Circuit Design

✓LED Power Considerations

✓LED Peak Wavelength Shift Compensation

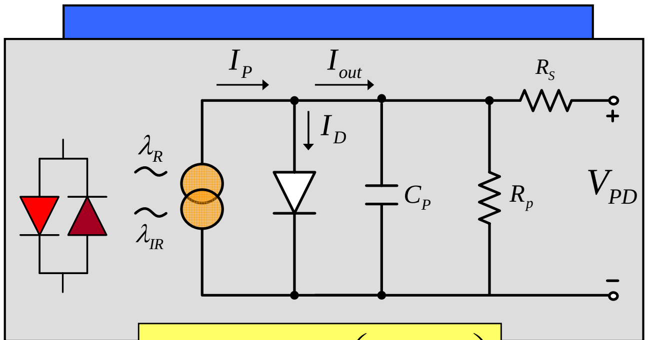
✓**Photodiodes and Transimpedance Amplifiers**

✓Improving Noise Rejection in Pulse-Ox Front Ends

✓Improving Dynamic Range in Pulse-Ox Systems

✓Choosing the ADC in Pulse-Ox Systems

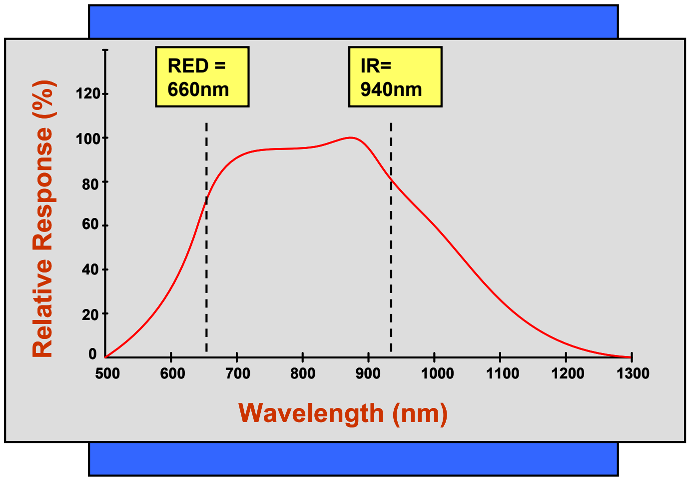
Pulse-Ox Photodiode Model



$$V_{PD} = \frac{kT}{q}\ln\left(\frac{I_P}{I_D}+1\right)$$

Shown here is the model for a photodiode showing the equivalent junction capacitance, shunt resistance, and series resistance. This presentation will not go into great detail about photodiode compensation.

Spectral Response of Si photodiode as a function of wavelength



Shown is a typical response of a photodiode in % vs. wavelength. At RED and IR the relative response is fairly high which yields output currents that can be more easily measured.

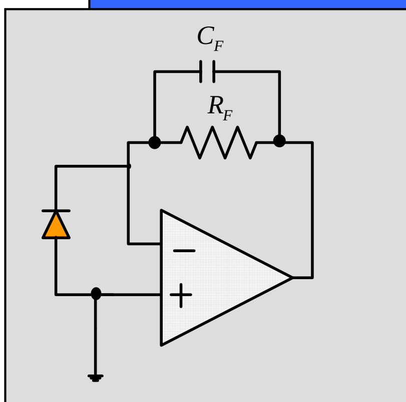
The Photodiode Transimpedance Amplifier Factors of Concern for Pulse-Ox

- Bandwidth
- Noise
- Power Consumption
- Offset
- Input Bias Current
- Dynamic Range
- Supply

44 of 81

Texas Instruments

Dissecting the Basic Single Supply Transimpedance Amplifier



- Increased R_F = Increased SNR
- Increased R_F = Decreased Bandwidth
- Large R_F = Small C_F = Wide Variation in 1/β DC Errors appear at output

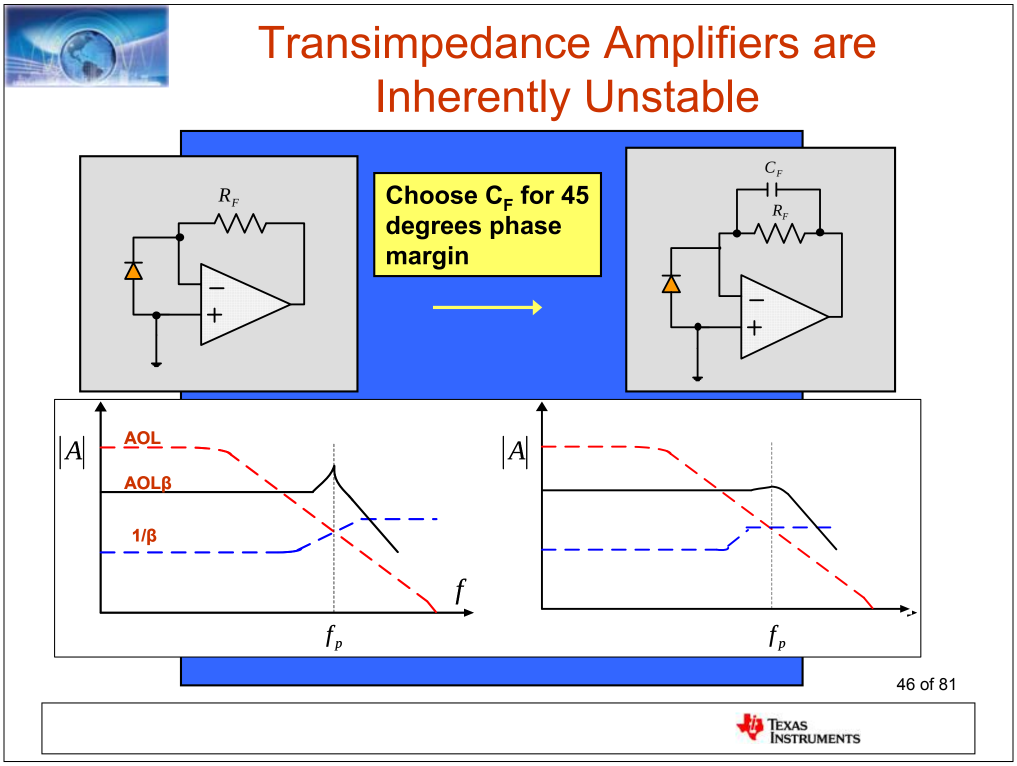
We will confine this discussion to the single supply configuration. Single supply is less expensive due to processing and smaller packaging; likewise, ADC's are commonly confined to the 0-5V range. The drawback on a linear transimpedance amplifier is that you have less dynamic range to work on the I-V conversion from the sensor because your supply range is confined to only 5V.

(1) Vbias is chosen at a minimum DC voltage to keep the amplifier within its minimum linear common mode range.

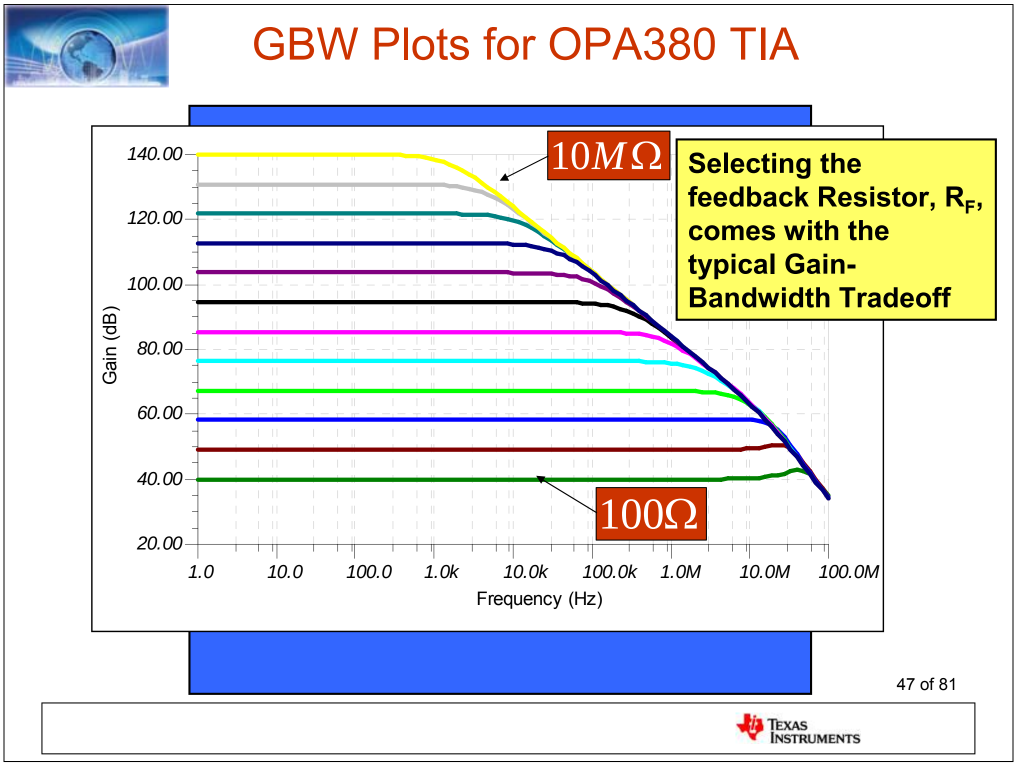
(2) RF is scaled to give a signal that at full scale input from the photodiode will not violate the output swing to the rail. The other compromise to be considered when selecting RF is that the larger its value, the lower the bandwidth of the transimpedance amplifier. This could be a problem if you are pulsing the LED at a frequency that is above this bandwidth.

(3) CF is a compensation capacitor that is necessary due to inherent transimpedance tendency to have a 40dB/decade intersection between the AOL curve and the 1/Beta curve. The 1/Beta curve increases in magnitude due to the differential and common mode capacitance off the inputs which inserts a zero into the 1/Beta transfer function. Proper selection of CF means that the 1/Beta curve will flatten with some margin before it intersects the AOL curve under worst case conditions.

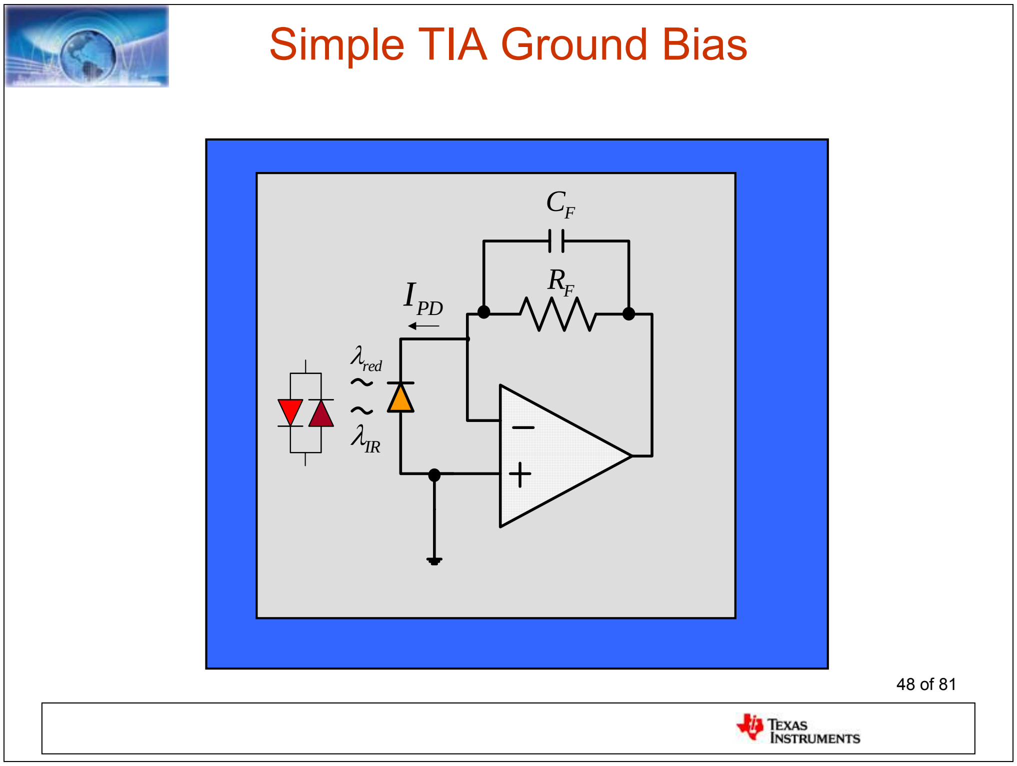
(4) Note also that the offset voltage, input bias current, and noise of the transimpedance amplifier will all appear as error on the voltage –converted output signal.



The reduction in peaking due to the compensation capacitor



Selecting the feedback resistor is critical as this is the stage where most of the entire system SNR is set; however, choosing a resistor that is too large may prohibit the input frequency signal bandwidth. Hence, there is a GBW tradeoff in gain and input signal bandwidth which will vary with system requirements.



Configuring the TIA with one input grounded has the following limitations:

VCM to GND Amplifiers

More Dynamic Signal Range

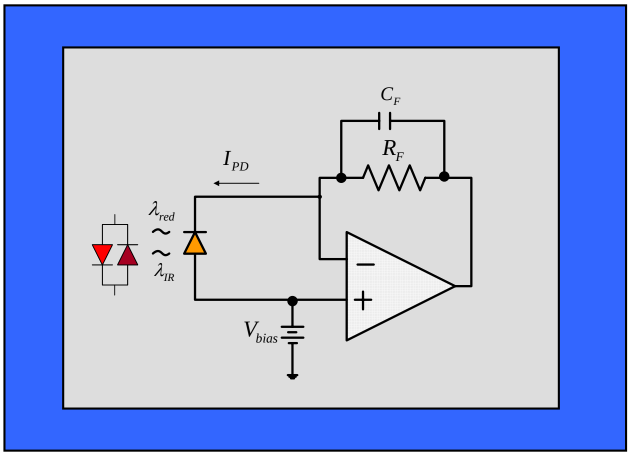
Susceptible to Ground Loops and DC Errors

Susceptible to Stray Capacitive Coupling

Careful Guard Traces at Summing Junction

Low Offset Required for Accurate Zero Scale

Simple TIA Reference Bias



$$f_{BW} = \frac{1}{2\pi \bullet R_L \bullet C_J}$$

$$t_R \cong \frac{0.35}{f_{BW}}$$

A bias voltage:

Minimum must exceed V_{CM} min

Limits Dynamic Signal Range at Output

Better rejection of Correlated Noise

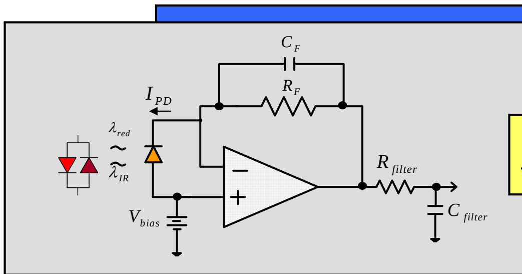
Reduces Stray Capacitive Coupling

Faster Photodiode Response

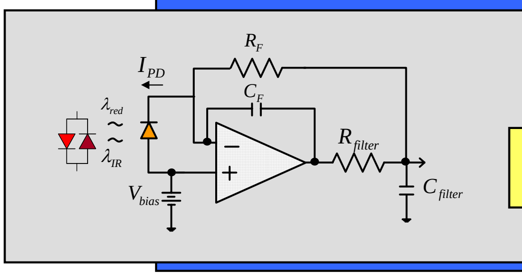
- ✓Biochemistry Background for Pulse Oximetry
- ✓Beer's Law: Empirical Understanding
- ✓Block Diagram for Pulse Oximetry
- ✓Pulse Sequence for LED
- ✓LED Circuit Design
- ✓LED Power Considerations
- ✓LED Peak Wavelength Shift Compensation
- ✓Photodiodes and Transimpedance Amplifiers
- **✓Improving Noise Rejection in Pulse-Ox Front Ends**
- ✓Improving Dynamic Range in Pulse-Ox Systems
- ✓Choosing the ADC in Pulse-Ox Systems

Texas Instruments

Proper Filtering Removes Noise in Trans Amp Stage

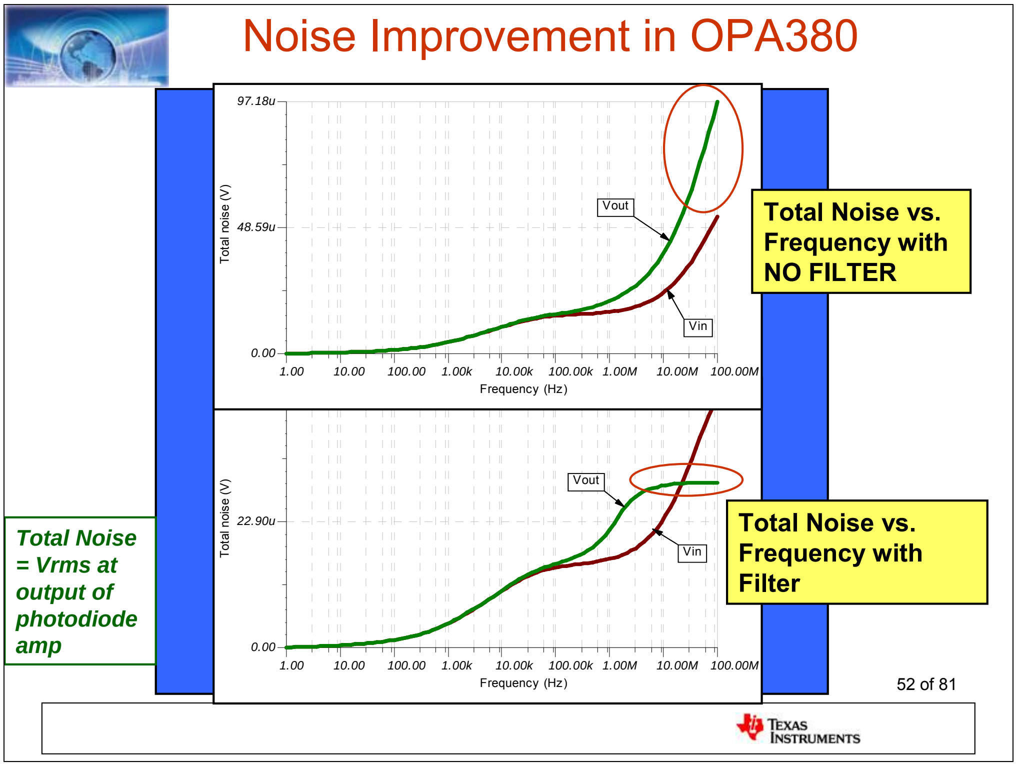


Requires Buffer Outside the Filter

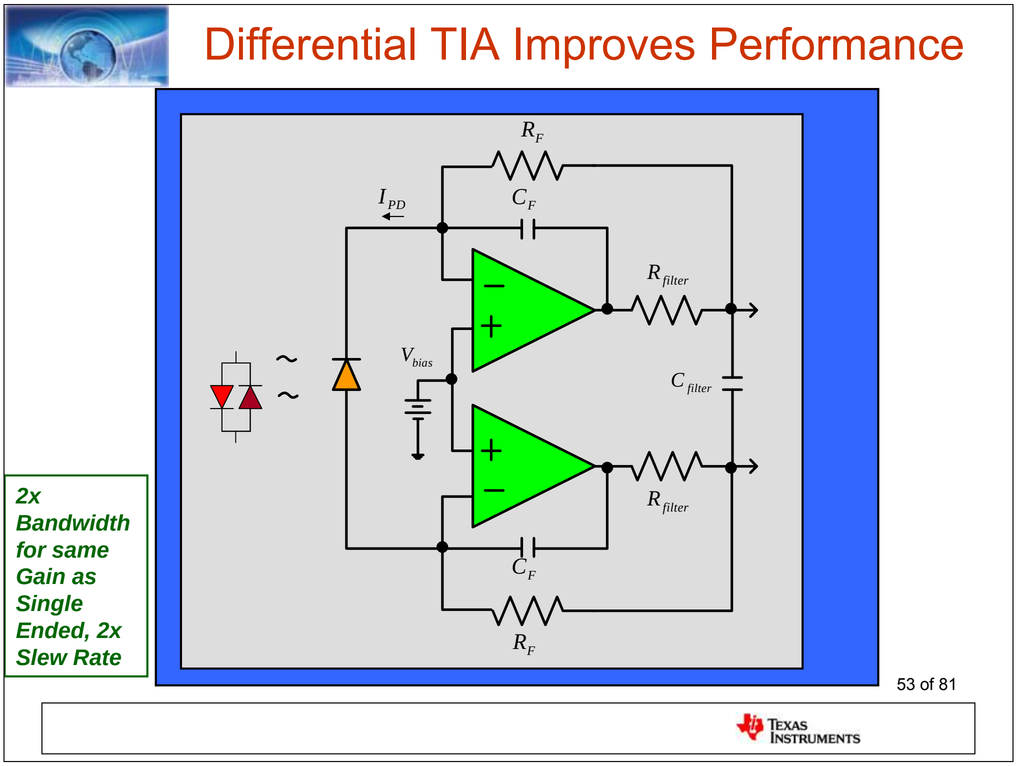


Filter in Closed Loop Maintains Low Z_{out}

It is advantageous in terms of SNR to try and achieve most of the gain needed in the first stage. Though it is not realistic in pulse oximetry to try and achieve all gain in this stage as the pulsed component only comprises 1% of the total photodiode current. Putting the filter inside the loop adds a free pole to the system without corrupting the bandwidth.

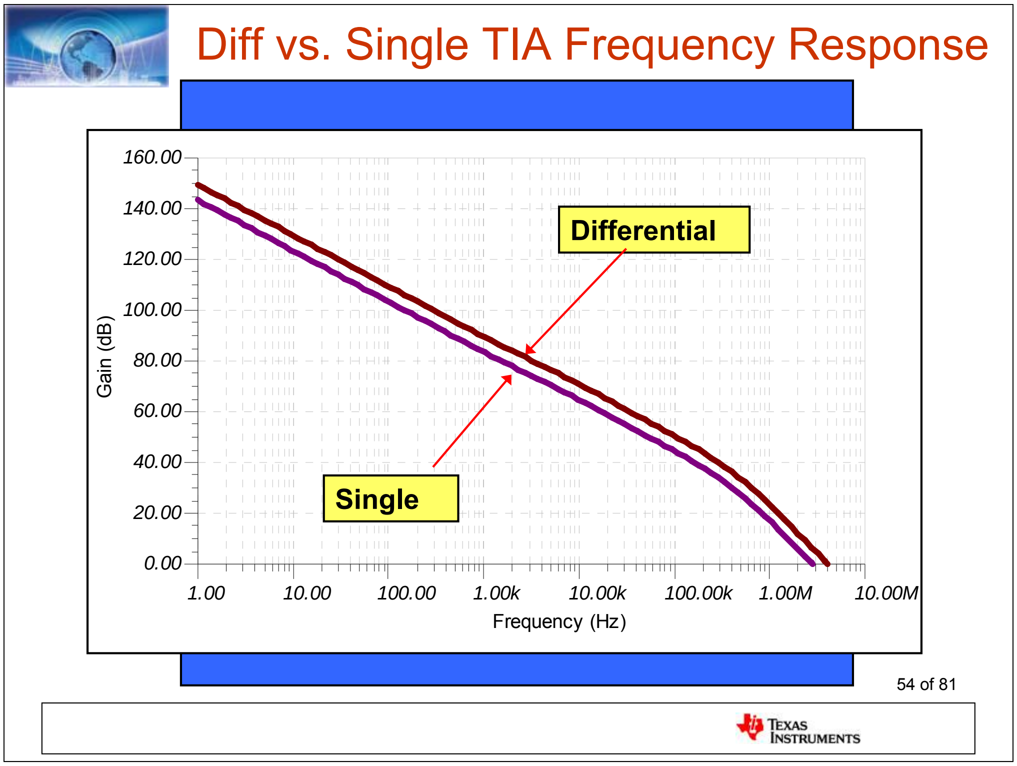


It may seem intuitively obvious that adding low pass filtering will decrease the noise at higher signal bandwidths; however, what may not be obvious is that this noise reduction does not have to come at the price of an additional buffer amplifier which would be necessary if this filter was placing OUTSIDE the loop.

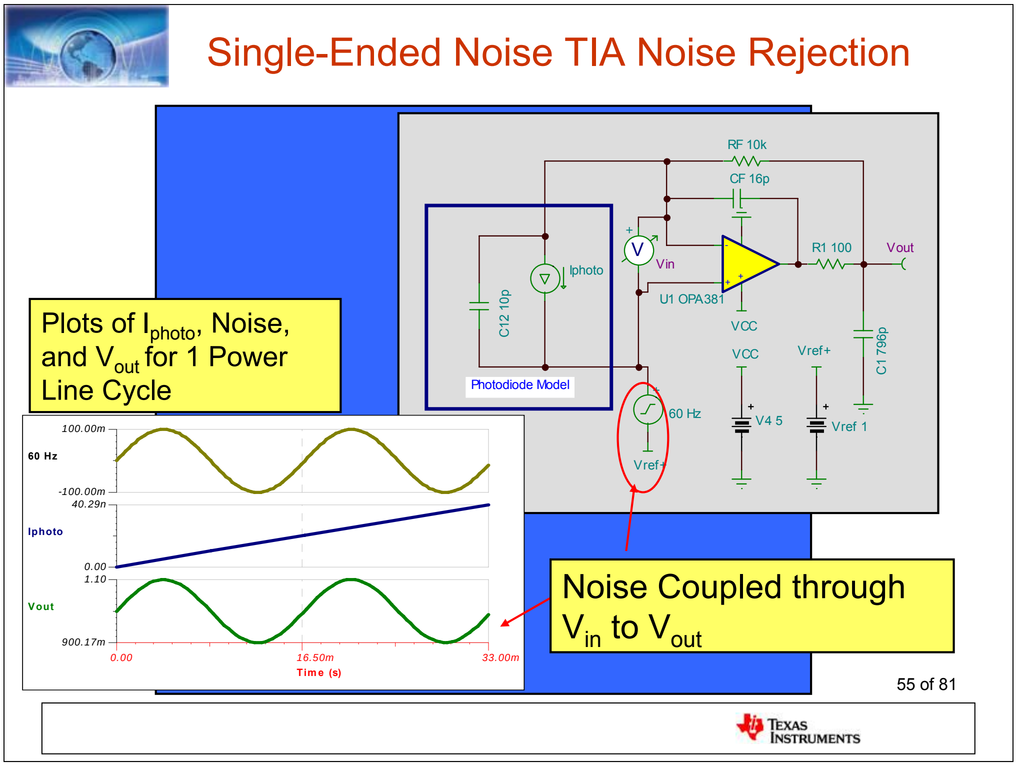


Using the Differential transimpedance configuration is superior in terms of gain and bandwidth. In fact, the gain is 2x that of the single configuration. Likewise for a given gain this configuration yields 2x the bandwidth as well. This is very important in pulse ox applications—high frequency noise will either be sampled and averaged out at the A/D converter and/or the filtering algorithms in the FPA, uC, or DSP. Even though the pulse width is only on the order of 5-2kHz, to take advantage of a good SAR converter (250KHz-1MHz sampling) is important make sure the signal is settled before being sampled. The faster the analog circuitry settles, the more time the converter has to sample and average high frequency noise.

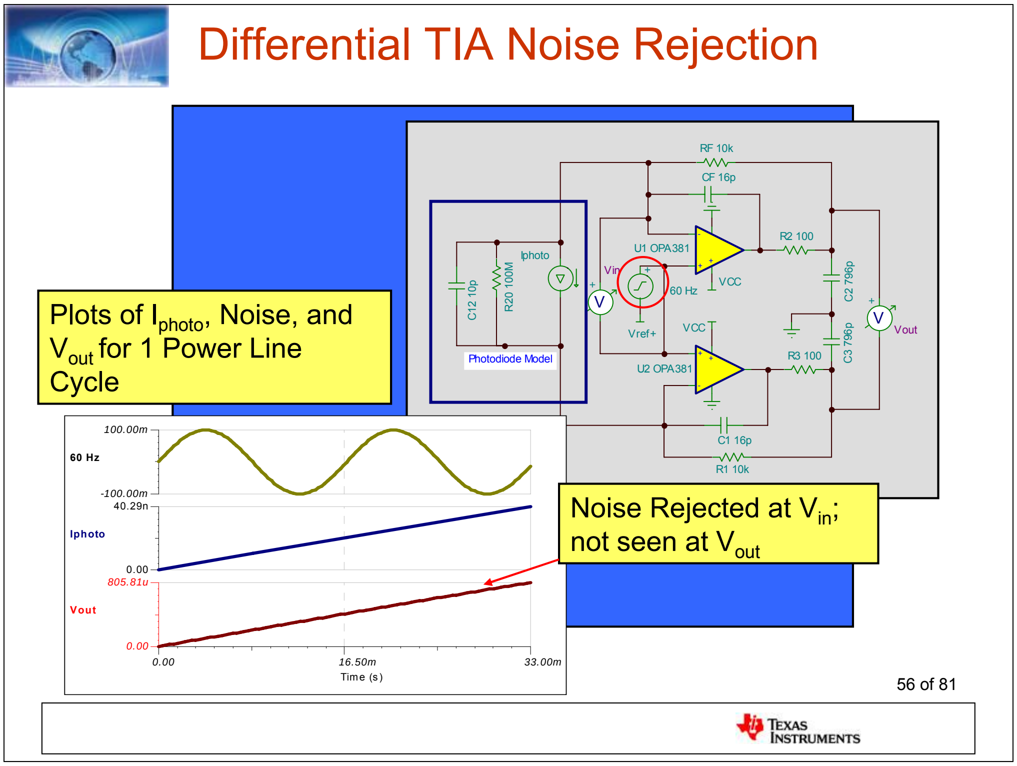
Pulse Oximetry is a marriage of the best of the biomechanical, physiological, and analog, and digital domain to yield the best information on SPO2 content. It is important to use every technique at our disposal to ensure that unwanted noise does not enter the circuit. This differential configuration helps in this fashion as noise that appears on the photodiode appears as common to the differential configuration; therefore, a common noise source will be rejected by the composite differential amplifier.



Adding a differential transimpedance stage helps with rejection of noise at the inputs because it makes it common to the difference signal; however, the inherent adding of additional components also adds to the overall noise.

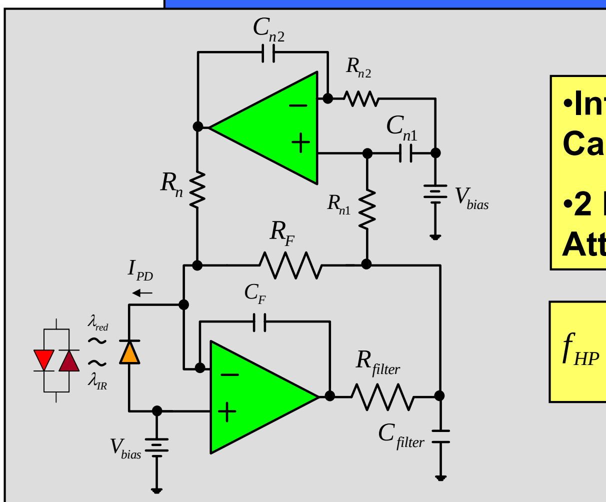


These plots show that noise coupled through the input at Vref translates itself directly to Vout.



In a differential configuration noise that appears at Vref gets rejected by the inputs and does not translate to Vout.

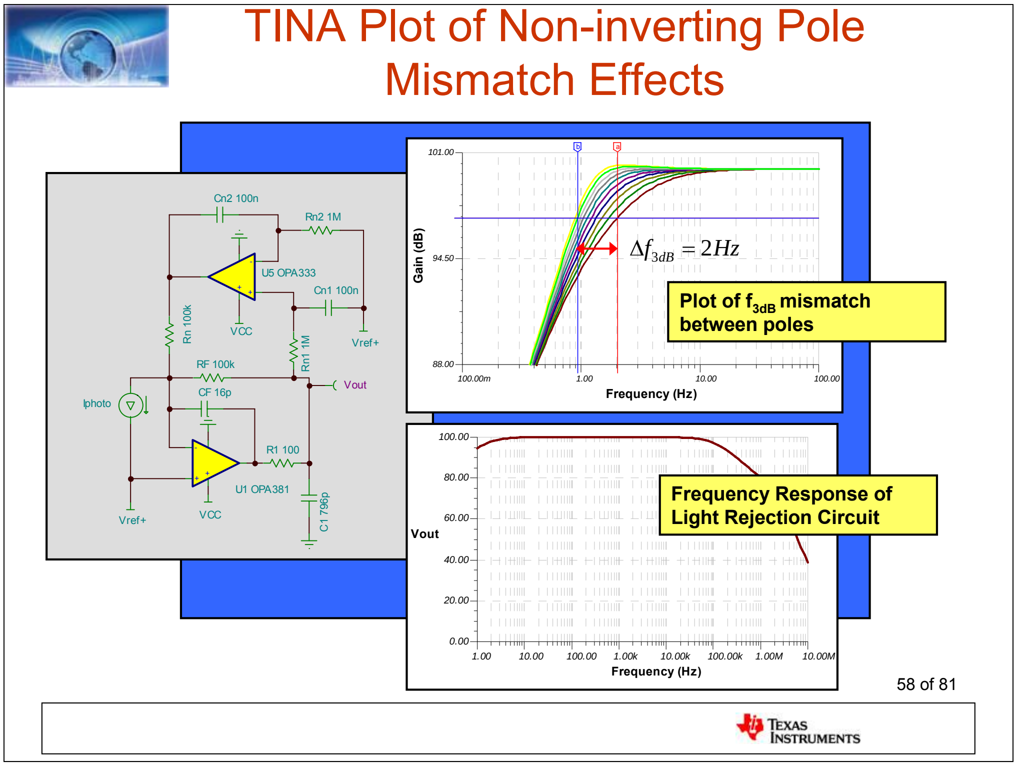
Ambient Light Rejection with OPA Servo Loop



- **Integrator Injects DC Cancellation Current**
- **2 Pole Filter For Higher Attenuation**

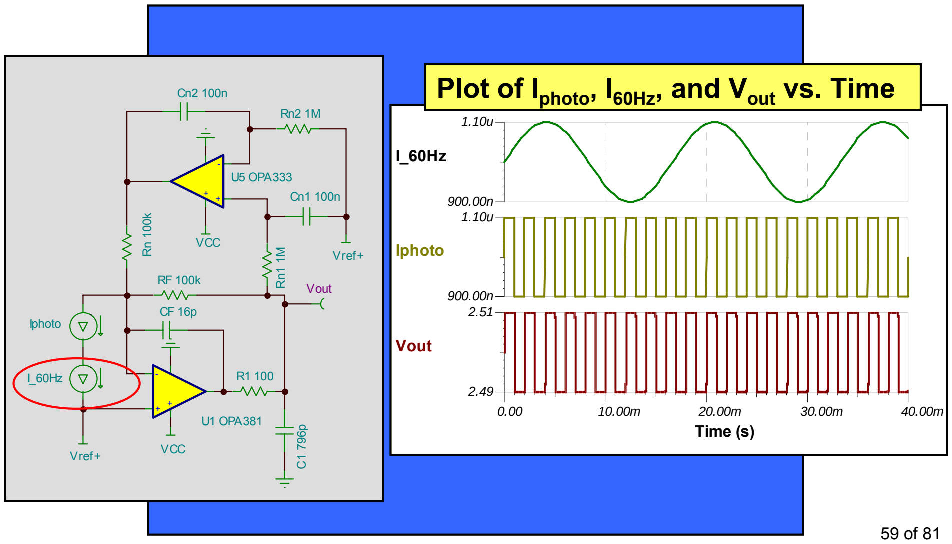
$$f_{HP} = \frac{R_F}{R_n \bullet \left(2 \bullet \pi \bullet R_{n2} \bullet C_{n2}\right)}$$

The feedback integrator in this circuit cancels out any DC components that are inherent at the inputs. The DC components may not just be the DC from the arterial pulse, but also from ambient light which can significantly reduce the overall system SNR. The integrator itself uses voltage feedback; however, since Rn is fixed to a virtual ground or virtual bias the integrator acts as a current servo which offsets the DC through the photodiode.



The 3bB cutoff frequency of the high pass filter should be set to reject 50 and 60Hz ambient light. Mismatch in the 2 poles will cause shift the 3dB point from a Butterworth response to a Bessel response. The low pass roll off is still determined by the inherent gain bandwidth of the transimpedance amplifier

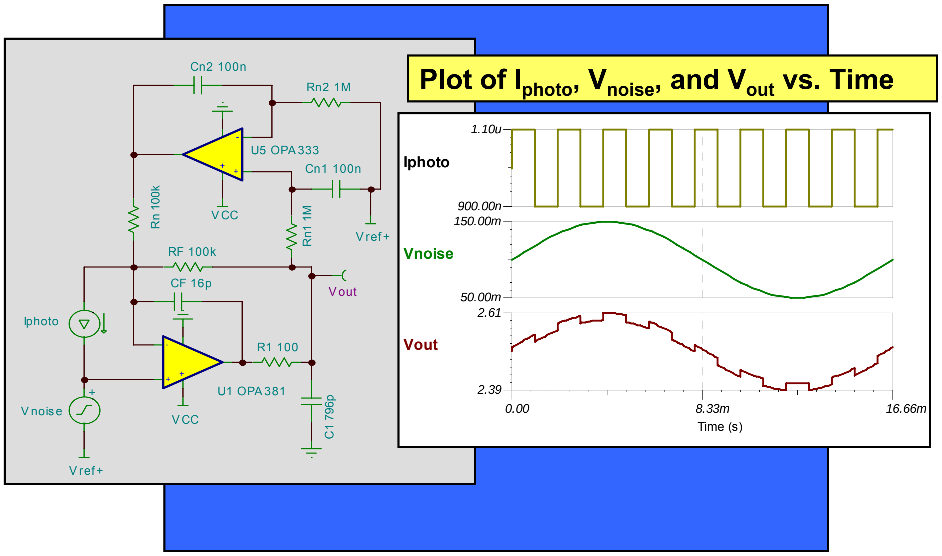
TINA Plot of Ambient Noise Rejection



Texas Instruments

This plot shows how 60Hz induced current is rejected at the output of the transimpedance amplifier

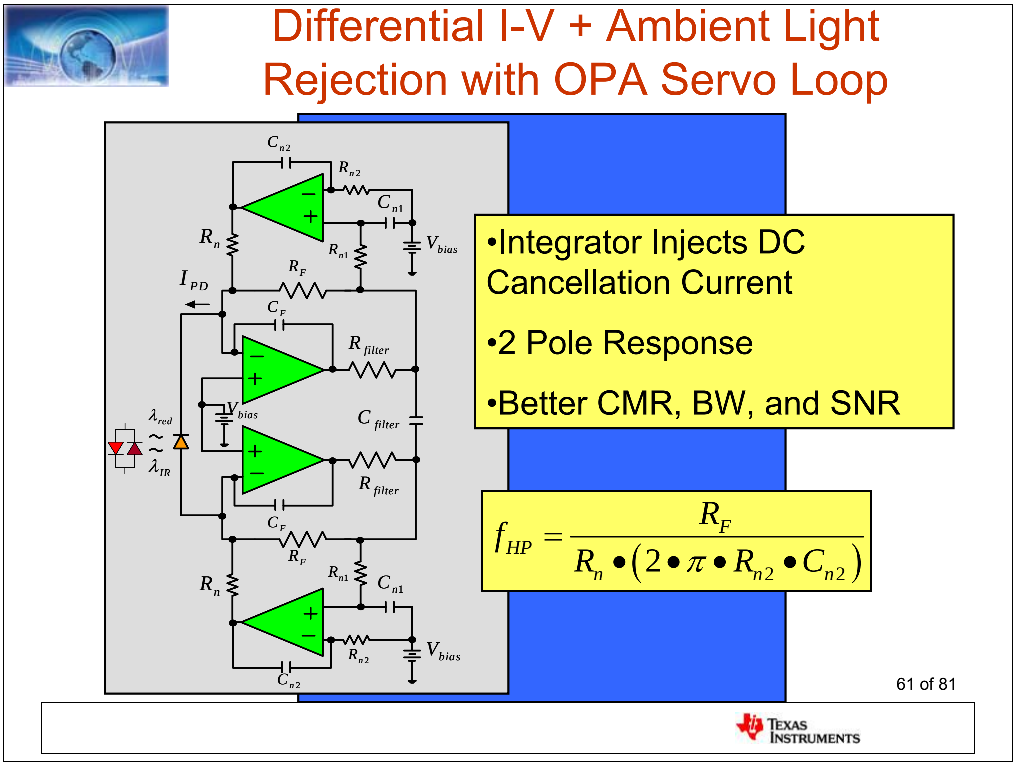
Noise at V_{ref} Translates to V_{out}



60 of 81

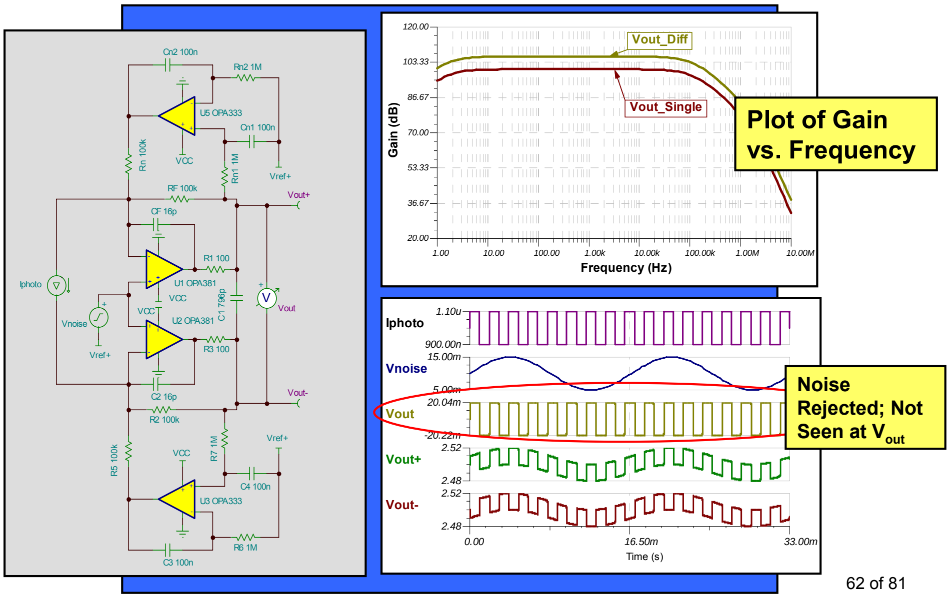
TEXAS INSTRUMENTS

The problem with the single-ended transimpedance amplifier is that voltage noise at the inputs can be seen at the output of the transimpedance amplifier. Though the example shown may be a bit extreme, this consideration should be taken into account in the design to minimize noise at the inputs on the reference pin.



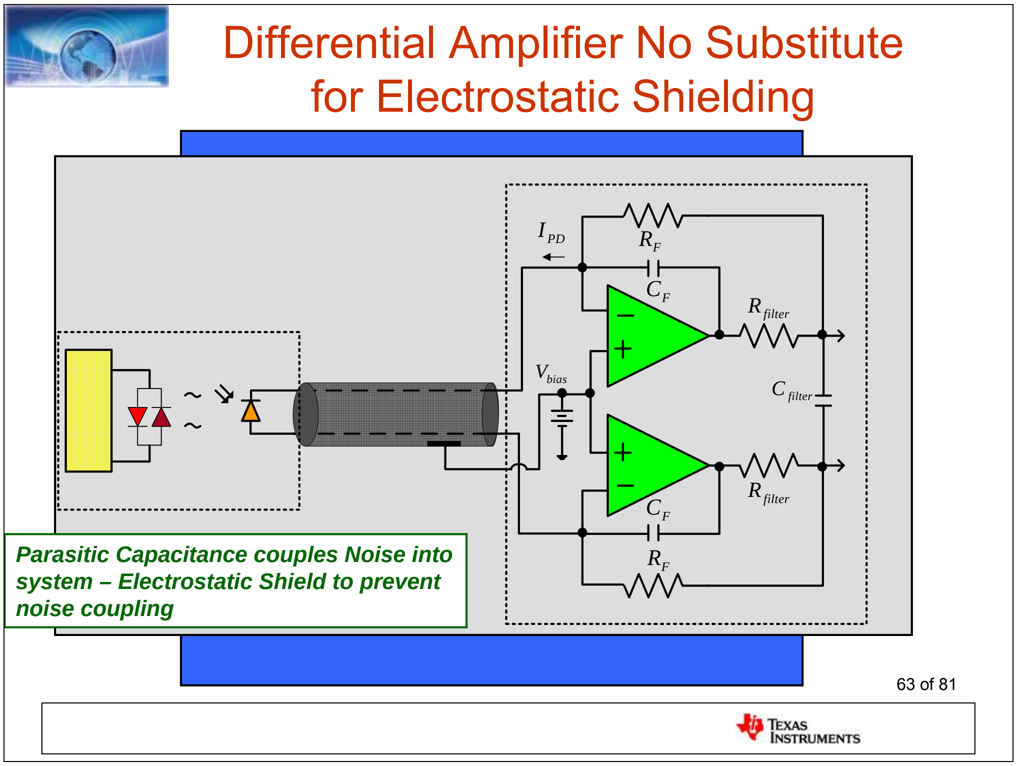
The essence of differential signal transmission is that it makes any noise present at the inputs common; therefore, most of the transmitted signal is due to the signal of interest (photodiode) and the noise gets rejected. The feedback integrators are important for reducing 60Hz pickup in the same way the RL drive works in an ECG common feedback system.

Differential Gain and Noise Rejection

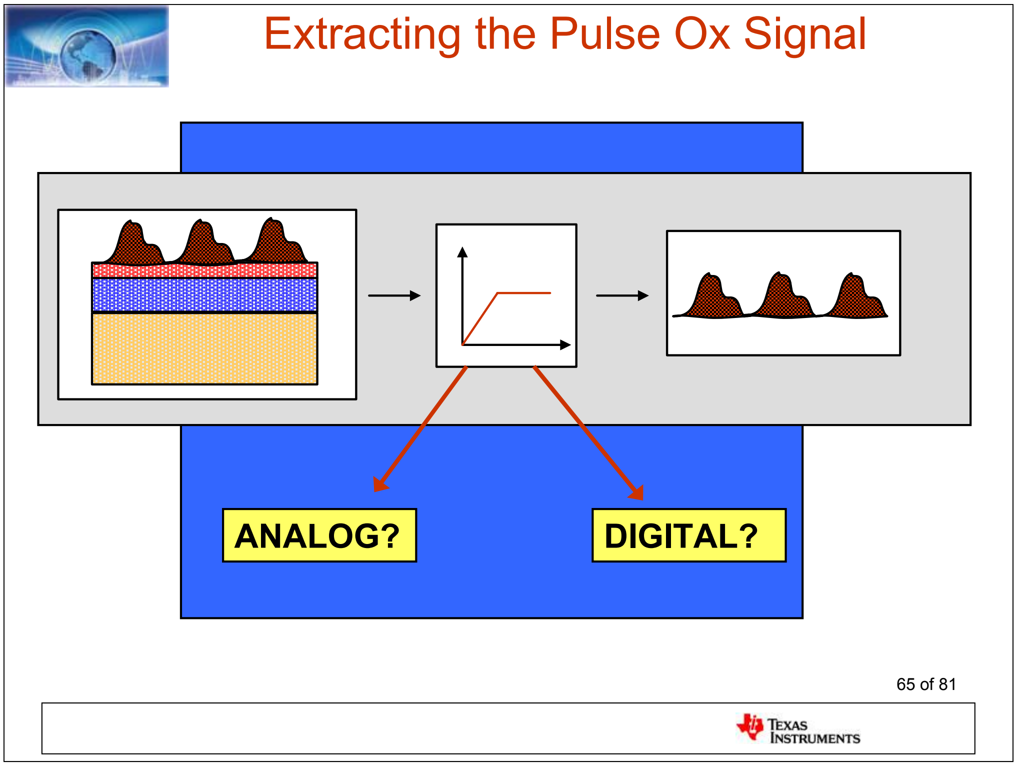


Texas Instruments

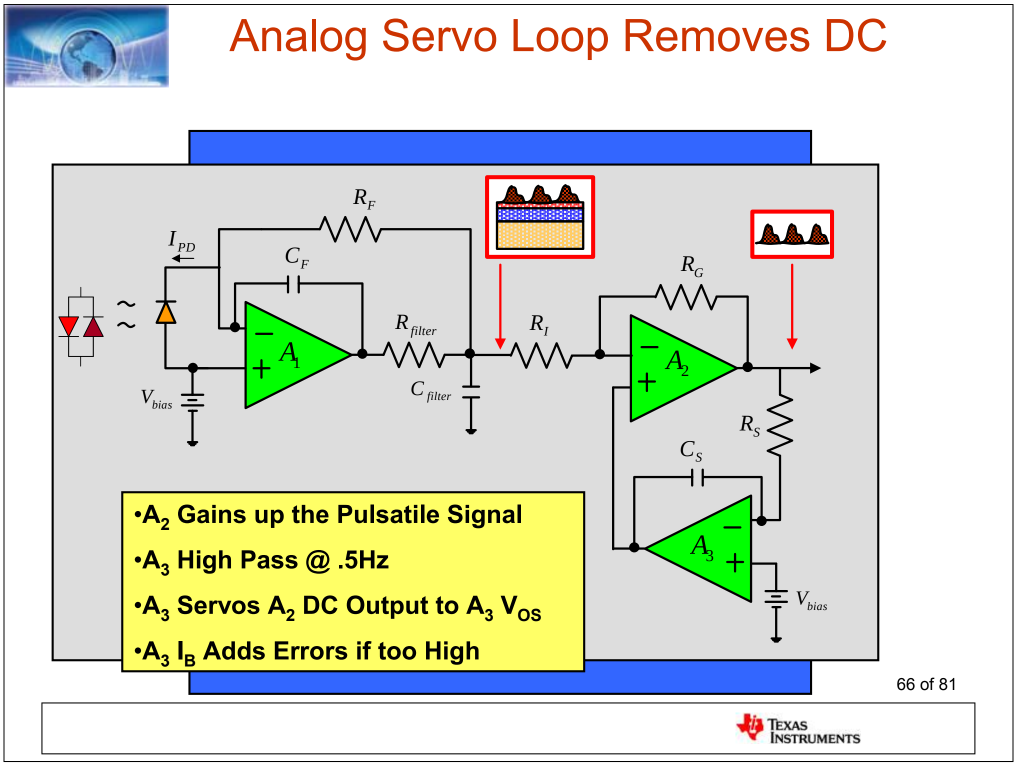
Shown here is the higher frequency pulse signal of interest riding on a 60Hz noise source. Since the 60Hz is common to both amplifiers the only signal that is translated to the output is the photodiode pulse. Also shown is the amplitude difference for a given photodiode current between a single transimpedance configuration and a differential transimpedance configuration.



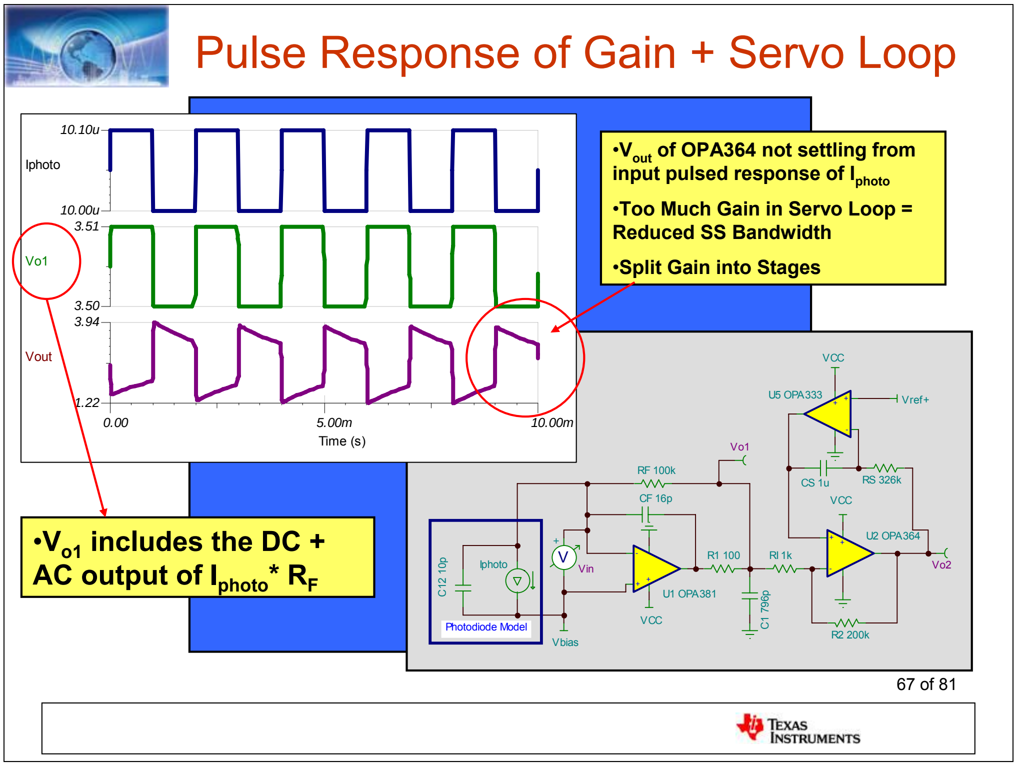
Parasitic capacitance is one of the most common channels for coupling electrical noise into a system. Putting an electrostatic shield around the connection of the photodiode to the transimpedance amplifier confines noise to a small region and creates a return path that when properly connected shunts noise away from sensitive electric components. Connecting the shield to more than 1 point can induce a noise potential across the shield in which current can flow. Also, the wires connecting the reference potential to shield and then to ground must be kept low to minimize inductance.



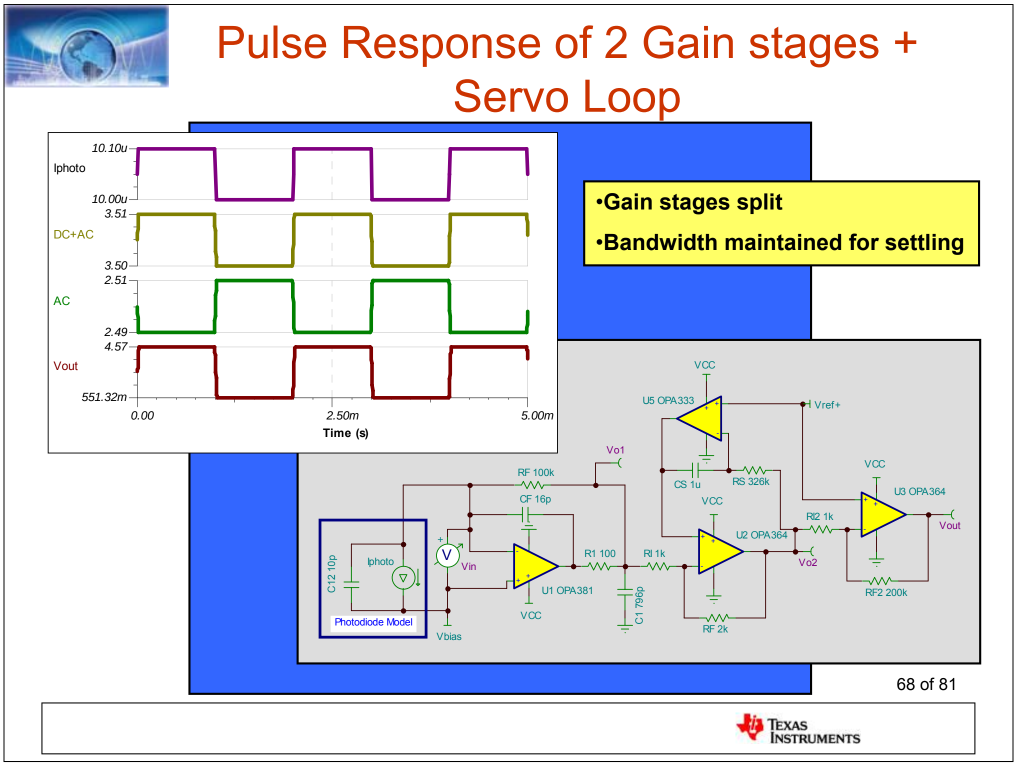
This section will focus on the removal of the DC component of the pulse ox signal. The reason that this is important is because the AC portion of the signal usually only comprises about 1% of the total pulsatile signal. Removing the DC component allows the AC component to be gained up in the successive signal chain such that the maximum amount of signal can be digitized by the ADC. The composition of this DC component is not only due to the physiology of the pulsed medium, but also due to gained up offsets in the signal path. Where and how to remove DC offsets is very application-dependent.



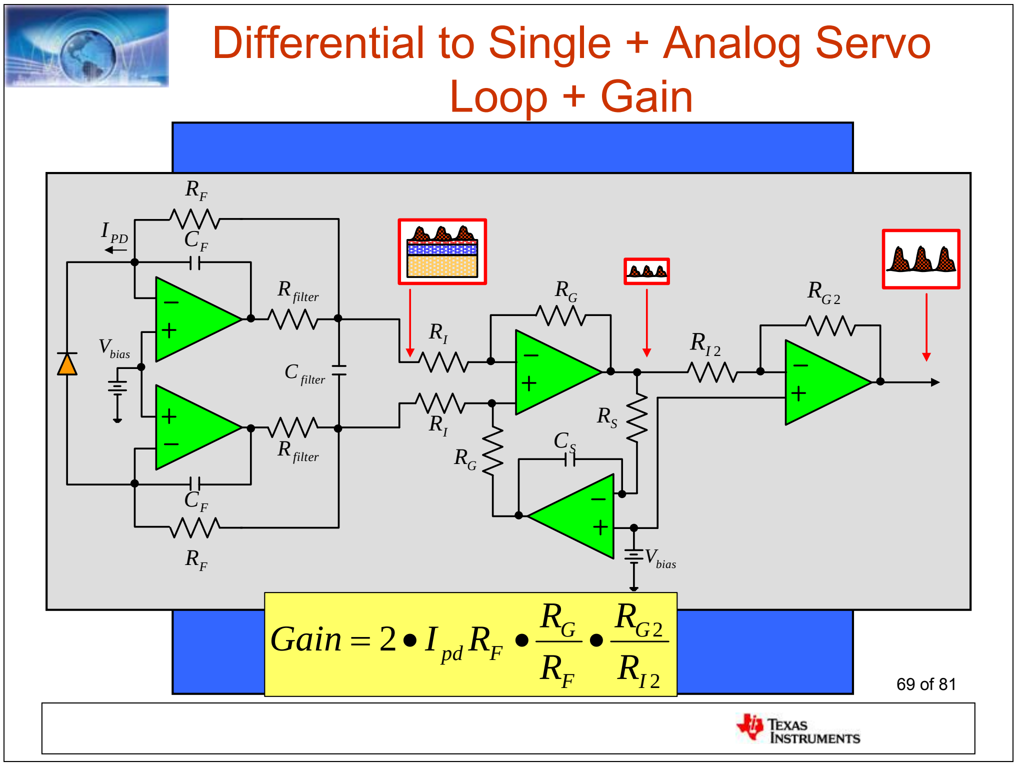
Removing the DC in analog often involves an analog servo loop. The servo amplifier does not have to be fast, but it should have precision characteristics such as low offset and bias current. Since low frequency information is important the time constant, essentially 2*pi*Rs*Cs, is very low in frequency. The downfall of using the analog servo loop is this very time constant—it can be very slow and it may take a couple of seconds to achieve an accurate reading.



If an integrator is used as a high pass filter, it is important NOT to try to do too much with this stage. In this case, if gain is too high the action of the servo amplifier and the GBW of the gain amplifier will not allow the signal to settle within the given pulse period.



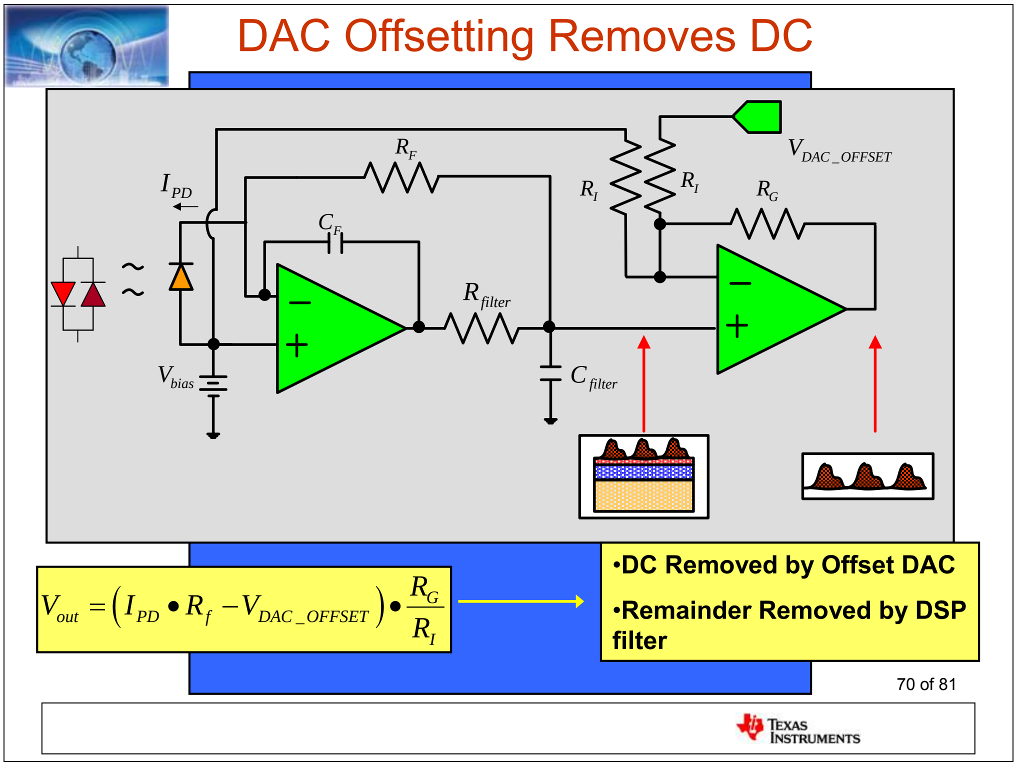
In this case the DC is removed by the integrator and is gained up by a subsequent stage. The gain of each subsequent stage is dependent on the pulse frequency—too much gain will limit the SS bandwidth and not allow the signal to settle within the pulse period.



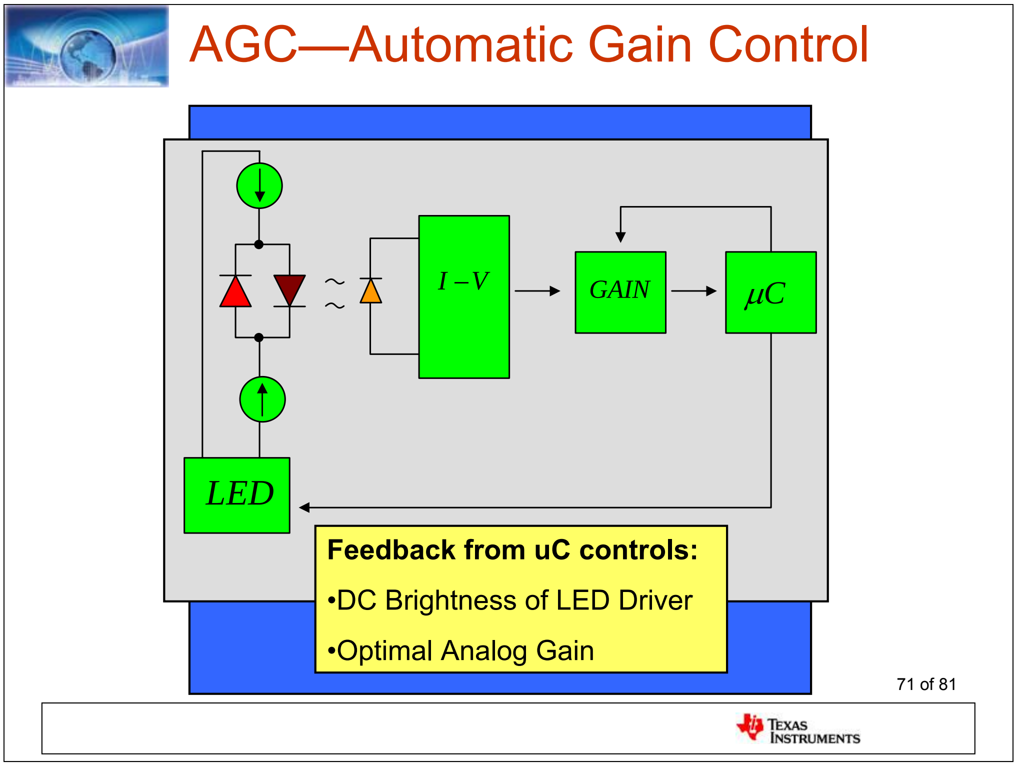
LPF added on gain stage with RC 10x pulse rate

High Frequency noise filtered with DSP and ADC sampling

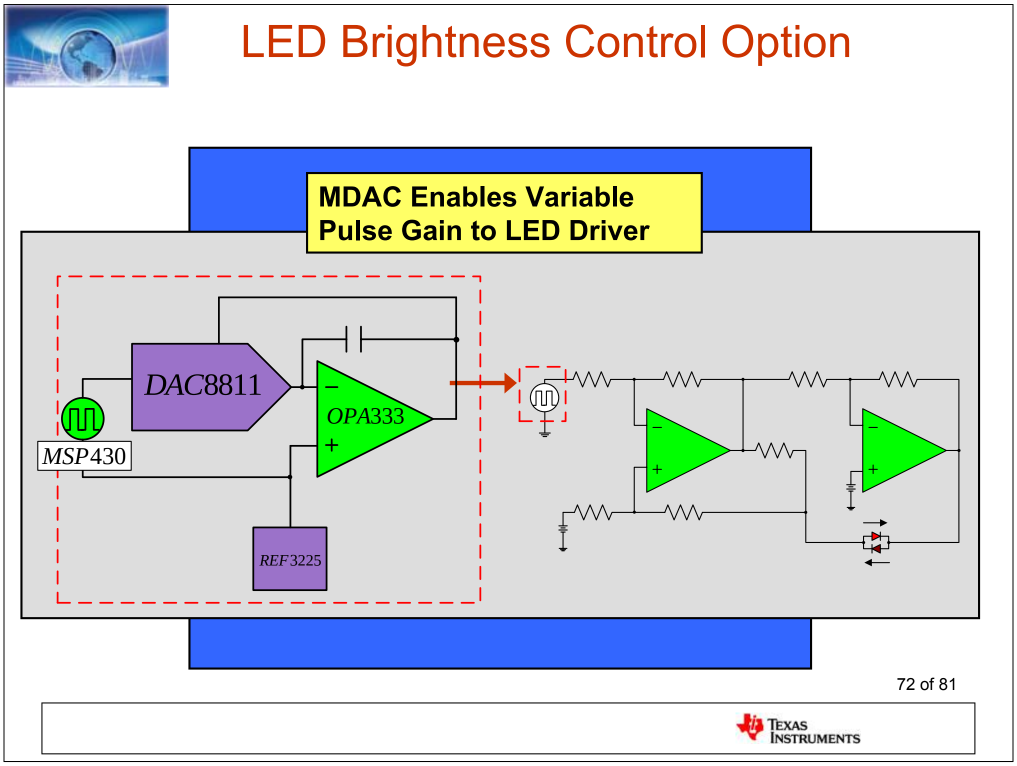
Servo Amp can be made higher order Bessel or Butterworth; tailored based on application needs



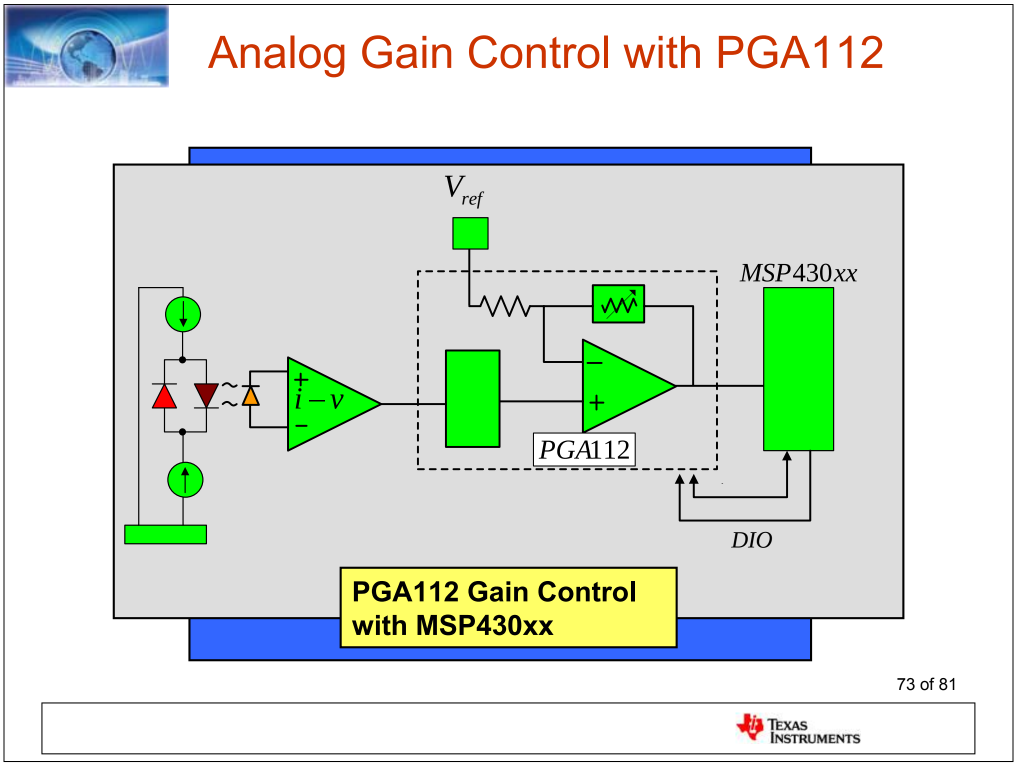
Sometimes it is preferable to feed back a DC offset voltage with a DAC from the signal processor which eliminates most of the DC component of the pulsatile signal. The remainder is removed with filtering in signal processing. This approach may be faster and more convenient for retaining the actual value of the original DC content.



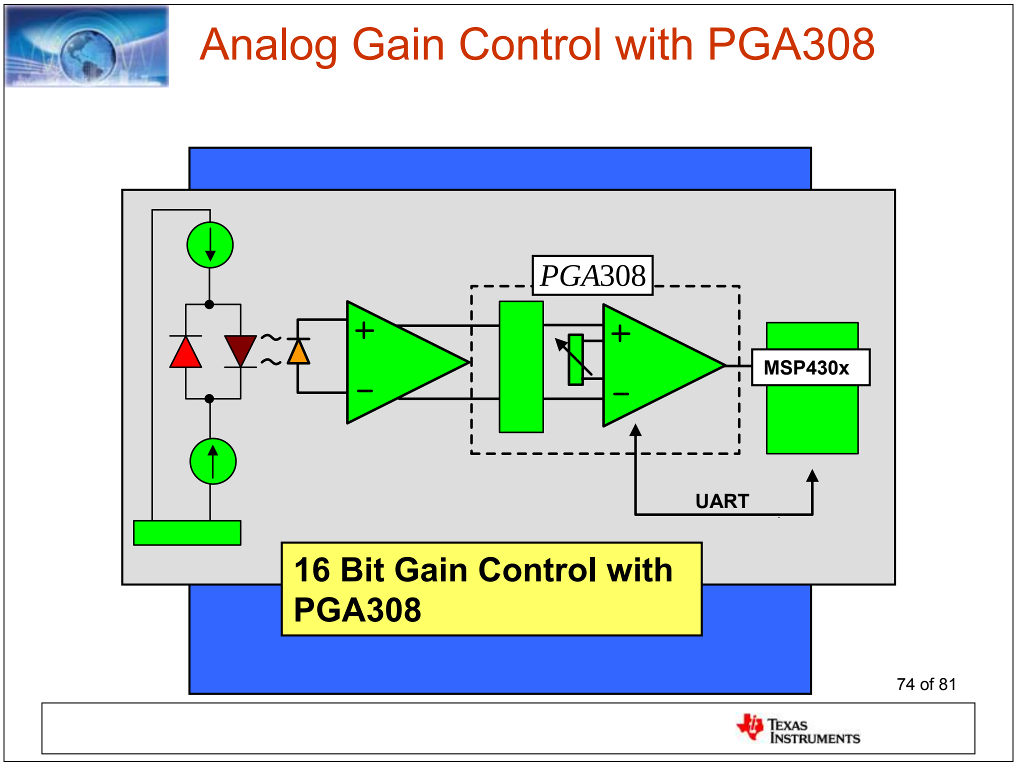
Though the DC and pulsatile component may remain relatively constant over short time periods, they may drift significantly over larger time intervals. Also, other various physiological changes as well as a shift in probe position can drastically effect the amount of signal that gets digitized at the output. This can be overcome through AGC. AGC or “automatic gain control” in Pulse Ox systems done through modulating the DC brightness of the LED driver or the discrete gain of the signal path through a programmable gain amplifier. The algorithm that is used to determine how much DC is added or subtracted to the LED driver vs. the signal chain gain path is usually a function of the proprietary sensor and its capabilities.



One method for creating and dynamically adjusting a precision level for LED input pulse is through the use of a multiplying DAC such as the DAC8811, a precision reference, and an precision amplifier such as the OPA333 or the OPA335. If the pulse is fast enough the OPA333 and/or OPA335 GBW may not be sufficient in which case a non-auto zero, high precision amplifier such as the OPA364 may be useful.



For a single-ended transimpedance output a good option might be to use the PGA112 to dynamically adjust the gain of the signal chain. The PGA112 runs off of a single supply and its gain can be controlled through SPI communication.

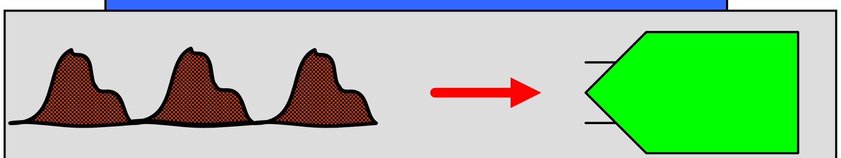


For a differential TIA output configuration, one possible option for programmable gain could be to use the PGA308. This device is extremely unique in that it is high precision, auto-zeroed, and its gain can be step controlled in 16 bit increments. Also, this particular PGA has a zero DAC which allows the elimination of DC; likewise, a coarse offset adjust DAC which allows +/-100mV of additional offset adjustment. This PGA gives added flexibility for more complex pulse-ox systems that also modulate pulse frequency, in which optimizing the GBW of the AGC block can become very complicated.

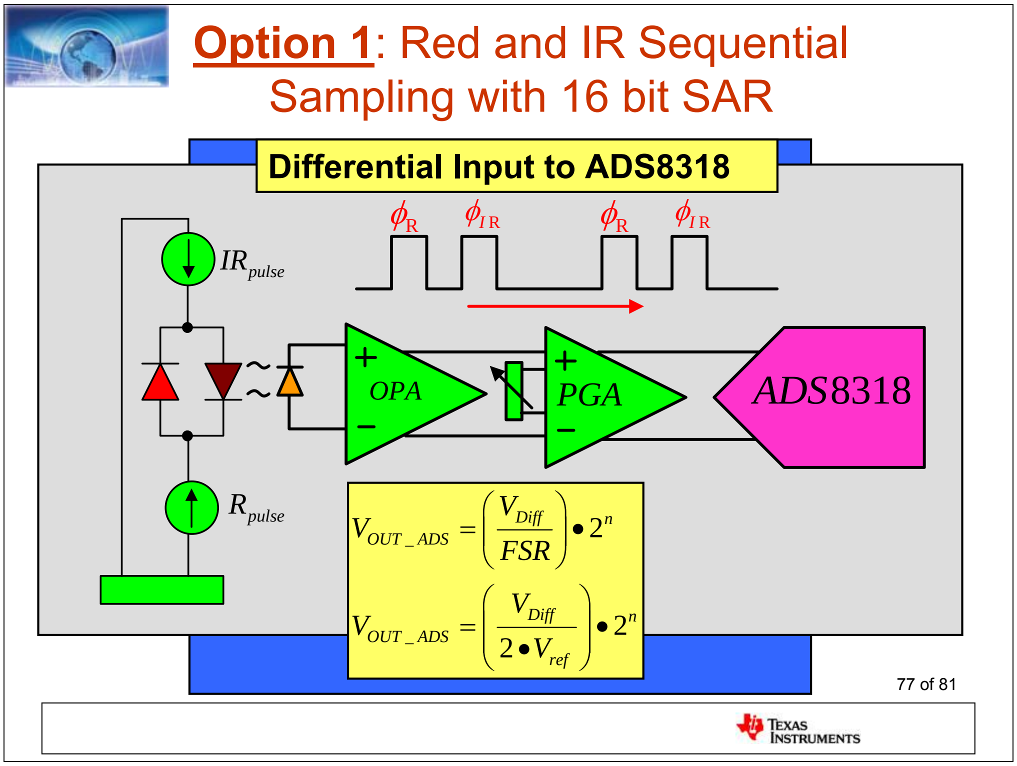
- ✓Biochemistry Background for Pulse Oximetry
- ✓Beer's Law: Empirical Understanding
- ✓Block Diagram for Pulse Oximetry
- ✓Pulse Sequence for LED
- ✓LED Circuit Design
- ✓LED Power Considerations
- ✓LED Peak Wavelength Shift Compensation
- ✓Photodiodes and Transimpedance Amplifiers
- ✓Improving Noise Rejection in Pulse-Ox Front Ends
- ✓Improving Dynamic Range in Pulse-Ox Systems
- → **✓Choosing the ADC in Pulse-Ox Systems**

Basic Pulse-Ox Considerations for the ADC

- •Number of Channels
- •Number of Wavelengths
- •Bits of Resolution
- •Throughput Rate/Bandwidth
- •Power Consumption



TEXAS INSTRUMENTS



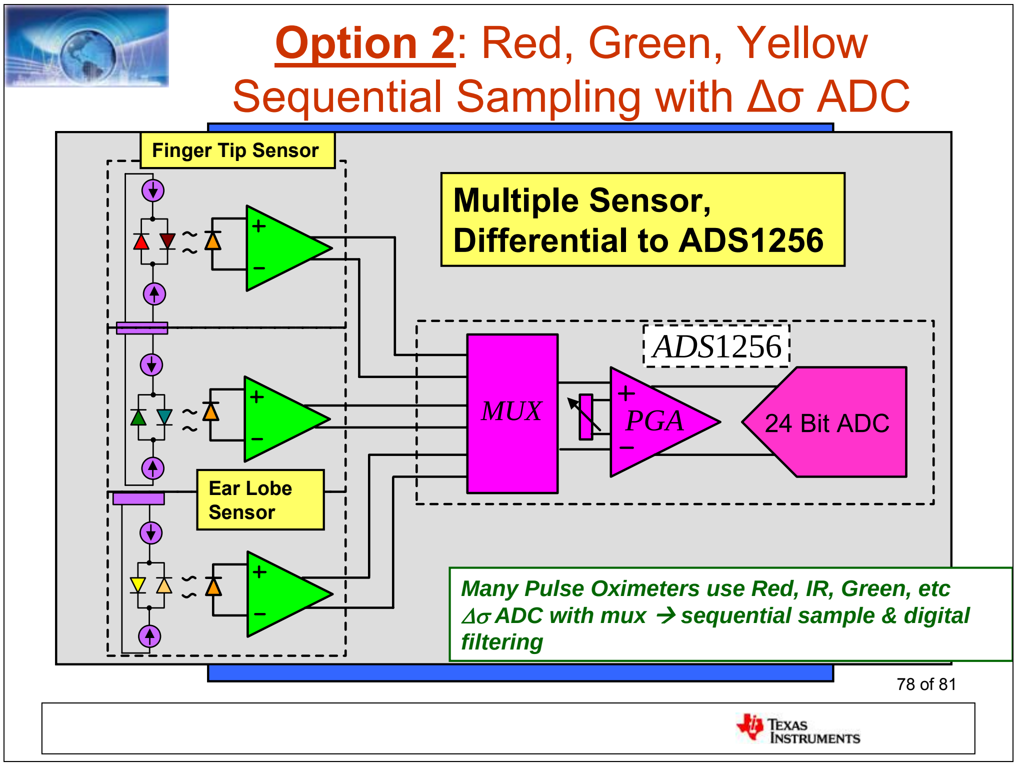
The advantage of using the same signal path for the red and infra-Red pulses is the following:

(1) The offsets subtract out because the calculation is a ratio of the red and infrared signal

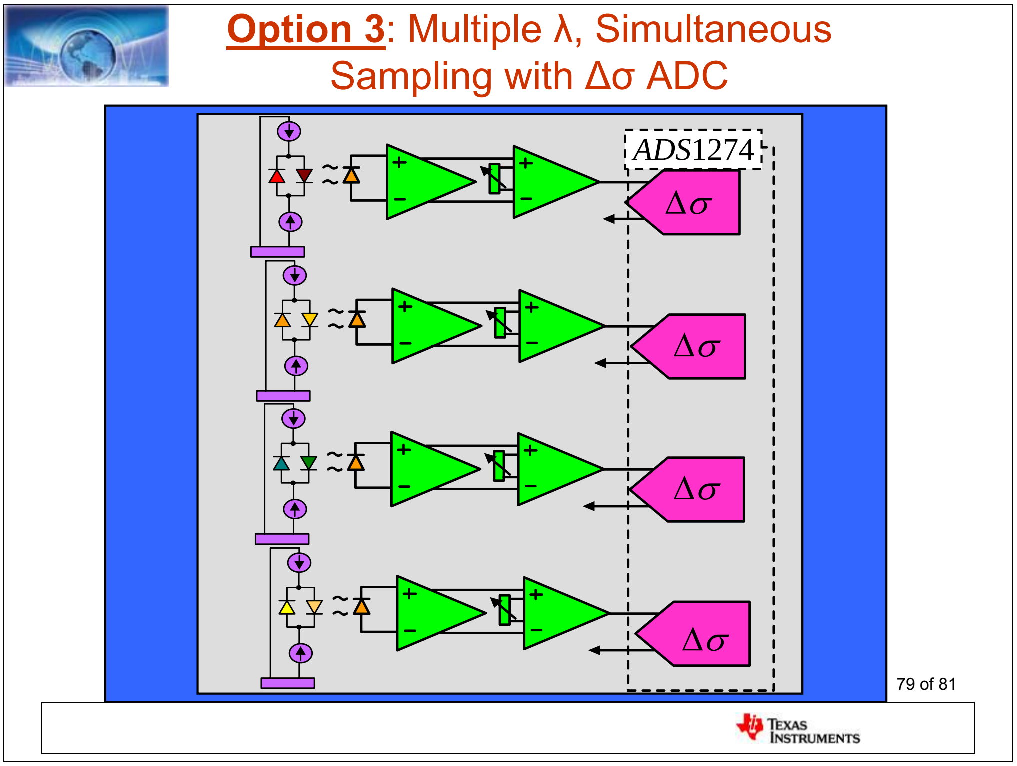
(2) The component count is minimized

(3) Keeping the signal differential purchases 6 dB i.e. (20*log(2)) of signal which increases the total SNR of the measurement

One disadvantage of the single signal path is that it is not quite as versatile. Many manufacturers produce their own customer photodiode sensors that use more than 2 wavelengths. In this case processing time for 4 consecutive wavelengths could become very long; therefore, a high speed ADC is needed to circumvent this. Higher speed ADC's usually burn a higher amount of power to the point where it might exclude it from a portable application.



Most modern pulse oximeters do not just employ Red and IR sensors; rather, they incorporate other wavelengths such as green along with proprietary excitation and algorithms. As a result, more than 1 photodiode sensor is required that is specific to each wavelength of concern. The ADS1256 allows the user to MUX these signals through the same signal path. Using a delta sigma converter may also mean that there does not have to be as much stringent DC stripping prior to digitization as the number of noise free bits yields sufficient resolution of the AC component that it may be removed with digital filtering.



More complex oximeters may use a large number of LED's with as many as 4 photodiode senors which are sensitive to particular bands of wavelength. The ADS1274/78 enable the outputs of each photodiode to be read simultaneously and sent to an FPGA, uC, or DSP for processing, filtering, and optimizing.

Conclusions

- Differential TIA provides more SNR
- Integrating Feedback Eliminates Ambient Light
- Choice of DC Filter Analog or uC/DSP Application-Dependent
- Feedback of LED Brightness and Analog Gain Optimizes Pulse Ox Signal
- Compensation for DC Offset Drift and LED Shift Minimizes Errors
- Choice of ADC Strictly Application-Dependent

References and Acknowledgements

- Beraducci, Mark and Soundarapandian, Karthik. Sbaa160, Application Report: *Analog Front End Design of ECG Systems Using Delta-Sigma ADCs.* March 2009.
- Fraden, Jacob. *Handbook of Modern Sensors—Physics, Designs, and Applications.* Advanced Monitors Corporation. San Diego. 2004.
- Franco, Sergio. *Design with Operational Amplifiers*. McGraw-Hill Inc. NY. 1988.
- Graeme, Toby, Huelsman. *Operational Amplifiers—Design and Applications.* McGraw-Hill Publishing Company. New York. 1971.
- Gray, Paul R. and Meyer, Robert G. *Analysis and Design of Analog Integrated Circuits.* John Wiley & Sons. New York. 1977
- Green, Timothy - Linear Applications Manager, general information
- Fredericksen, Thomas M. *Intuitive Operational Amplifiers.* McGraw-Hill Inc. 1988.
- Norton, Harry N. Sensor and Analyzer Handbook. Prentice Hall Inc. New Jersey. 1982.
- Stitt, Mark and Meinel, Wally. Application Bulletin : *OPT201 Photodiode-Amplifier Rejects Ambient Light*. Tucson, 1993.
- Townsend, Dr. Neil. “Pulse Oximetry,” taken from Medical Electronics, Michaelmas Term 2001.
- Webster, J. G. *Design of Pulse Oximeters*. Taylor and Francis Group. New York. 1997.

TEXAS INSTRUMENTS