

Signal Chain Performance Optimizations in the TI DLP® Technology-Based Spectrometer

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ABSTRACT

On a TI DLP® technology-based spectrometer, the individual elements of the signal chain combine together to determine the overall performance of the system. This application report describes the design considerations for all the components of the DLP technology-based spectrometer signal chain and the effect of their interactions on the overall performance of the system. The DLP NIRscan™ and DLP NIRscan Nano evaluation modules (EVM) are used as examples to discuss the tradeoff and optimization of spectrometer components. For an overview of spectroscopy and how DLP technology compares to existing technologies, refer to the DLP Technology for Spectroscopy white paper (DLPA048).

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1 Introduction

A near-infrared (NIR) spectrometer measures the light absorption of a substance using InGaAs photodiodes that generate a small amount of current when a photon impacts the P-N junction of the semiconductor. This current is digitized through a transimpedance amplifier and the absorption spectrum is computed. The following sections discuss the design considerations and noise sources in the signal chain of the components of a TI DLP technology-based spectrometer from illumination to the digitization of the photodiode signal.

2 Signal Chain Architecture of a TI DLP Technology-Based Spectrometer

In a TI DLP technology-based post-dispersive spectrometer, a sample is illuminated and the reflected light is collected. The diffusely reflected light from the sample is gathered by the collection lens and focused into the optical engine through the input slit. The light that passes through the slit is collimated, lowpass filtered, and then strikes a reflective grating. This grating disperses the light into its constituent wavelengths. The focusing lenses form a separate image of the slit for each wavelength at the digital micromirror device (DMD). Copies of this slit image are spread horizontally across the DMD at different wavelengths. A specific implementation of this optical architecture is in the [DLP NIRscan Nano EVM](#). [Figure 1](#) shows a cross section and interior view of this optical architecture. Refer to [Texas Instruments DLP NIRscan Nano Evaluation Module \(EVM\) Optical Design Considerations](#) for more information on key optical parameters of the lenses, filter, grating, and slit, and their interdependence on system performance and size.

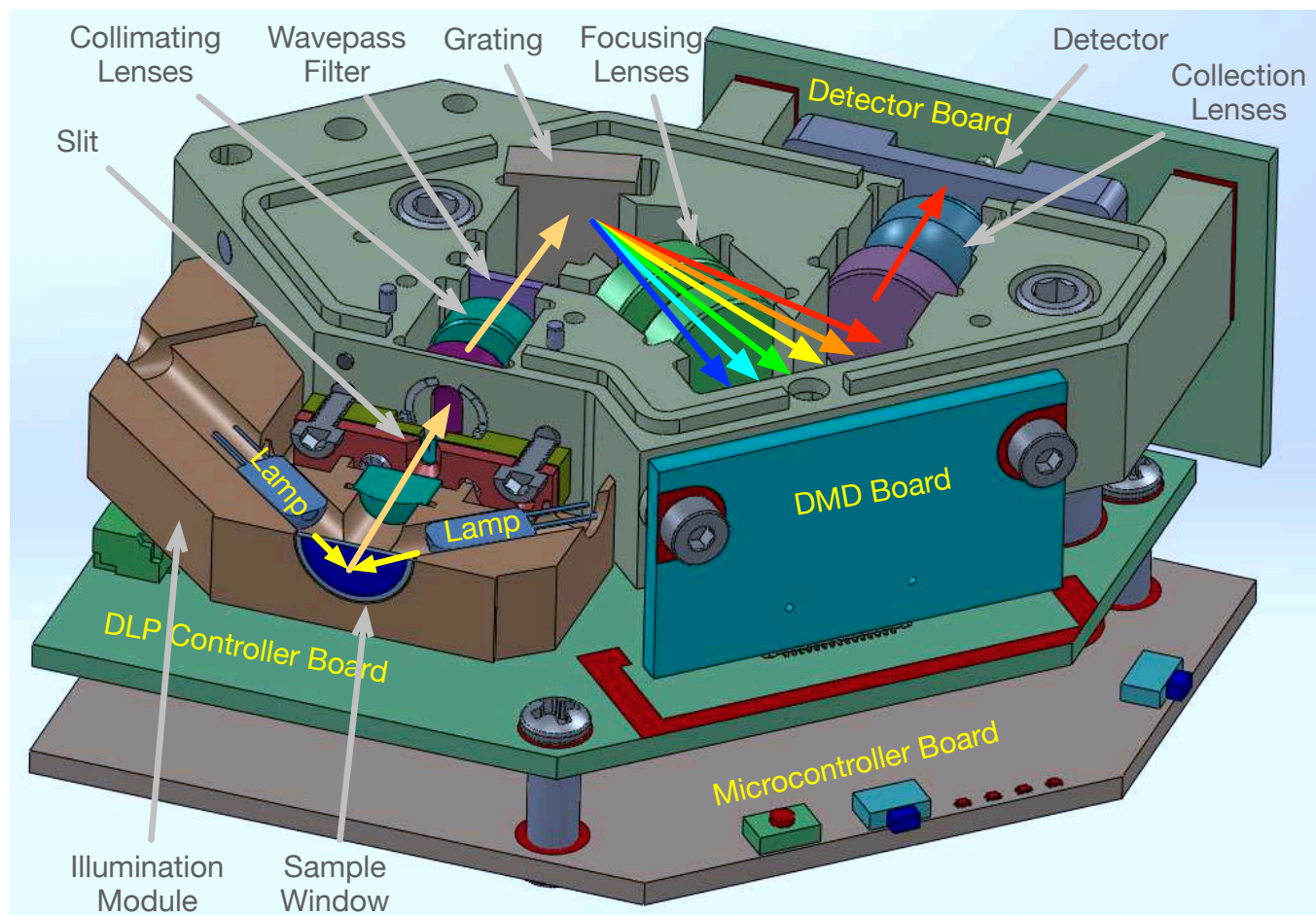


Figure 1. DLP NIRscan Nano Optical Architecture

In this optical architecture, the light energy from the grating is directed through the collection lenses into a single InGaAs detector when specific DMD columns are selected as "on". The width of the DMD columns selected as "on" determines the amount of light directed to the photodetector, as well as the resolution of the system. The collection lenses gather and concentrate the light energy onto the single point InGaAs photodetector. All other DMD columns selected as "off," divert the unselected wavelengths away from the photodetector optical path so as not to interfere with the measurement of the selected wavelength. The signal at the photodetector is amplified with a transimpedance amplifier and converted to a digital value through an analog-to-digital converter (ADC). Figure 2 shows a block diagram of the components of this signal chain components in a typical post-dispersive TI DLP technology-based spectrometer. The interactions and design parameters of the components in this signal chain combine together to determine the overall performance of the system. For a high signal-to-noise ratio (SNR), the designer must:

- Maximize the intensity of the illumination source while minimizing its noise,
- Maximize the size of the slit to maximize the optical power of the illumination through it,
- Minimize photodetector and analog noise while matching ADC dynamic range to the photodetector signal range.



Figure 2. Typical Signal Chain of a DLP Technology-Based Spectrometer

The illumination module generates the maximum amount of light that can be absorbed by the sample. The intensity and stability of light determines the maximum signal and initial noise of the system. On a reflective module, the light reflected by the sample is collected and passed through a slit. The slit width is chosen to balance wavelength resolution with SNR depending on the desired specifications of the system. The DMD is used to select specific wavelengths and direct them to a single point photodetector. The DMD accomplishes the wavelength selection through a set of patterns applied to the micromirrors. The sequence of patterns forms a scan configuration. Thus, the slit width, DMD array, scan configuration, and DMD column width influence the resolution and maximum amount of light on the photodetector.

Once the light is converted into an electrical signal (current) at the photodetector, the transimpedance amplifier converts the current signal into a voltage.. The gain and architecture of this transimpedance amplifier needs to match the maximum signal in the dynamic range of the ADC. Finally, the ADC converts the voltage into a digital representation of the signal. The ADC resolution and sampling rate impact the final accuracy of the system.

3 Design Factors

To optimize the signal chain, the following factors must be considered:

- System resolution
- Scan measurement time
- Maximum illumination power and stability
- Slit width
- Photodetector characteristics
- DMD array size, scan mode, and pattern width
- Maximum photodiode signal when exposed to light
- Transimpedance amplifier bandwidth and gain to match the ADC dynamic range
- ADC resolution, sample rate, and voltage references

3.1 Illumination

Tungsten halogen lamps are well suited as spectrometer light sources due to their broadband infrared radiation. The DLP NIRscan's transmissive illumination module includes an [ILT L8008](#) lens-end lamp and a lamp driver that provides a constant current of 750 mA at 5V. The light output of this lamp is sufficient for cuvettes with path lengths of 2-13 mm.

Alternatively, the DLP NIRscan Nano's reflective illumination module includes two [ILT 1088-1](#) lens-end lamps and a lamp driver that provides a constant current of 280 mA at 5 V. These lens-end lamps focus the light beam at about 3 mm away from the lamps and create a spot size that covers the sapphire sample window, as illustrated in [Figure 3](#).

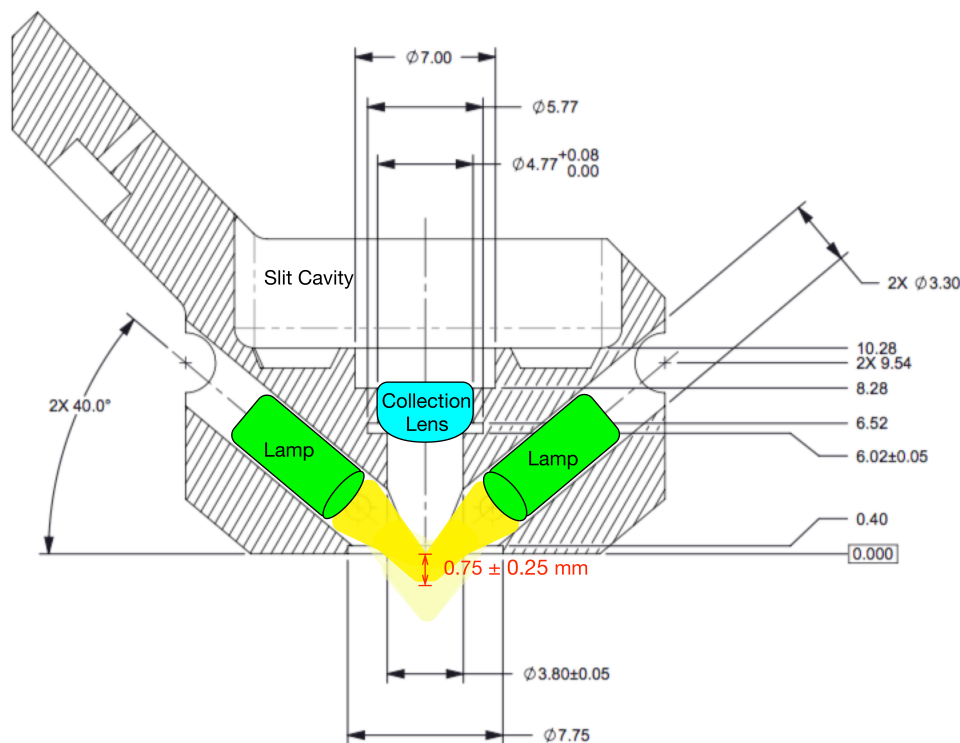


Figure 3. Top Cut-away View of DLP NIRscan Nano Reflective Illumination Module

Depending on sample preparation and presentation, some highly absorbent samples in the NIR region might not reflect sufficient light back into the system. For example, a sample with high water content can show high NIR absorption. For these highly absorbent samples, the DLP NIRscan Nano allows the flexibility of replacing the illumination module with a modified illumination module that includes lamps providing greater light output. Larger lamps would require changes to the lamp driver, illumination module optics, and chassis. [Table 1](#) provides a few examples of lamp options along with the size, power consumption, filament life hours, and focal distance from manufacturer data sheets. Note that lamps with reflectors are much larger in volume, but will direct light that is typically absorbed in the illumination chassis into the sample.

Table 1. Lamp Options for DLP NIRscan Nano

Lamp Model	Quantity	Power	Size	Filament Life Hours	Focal Distance
ILT 1088-1	2	2 x 0.14A @ 5V = 1.4W	3.18 x 6.35 mm	18,000	3 mm
ILT 1088-1	4	4 x 0.14A @ 5V = 2.8W	3.18 x 6.35 mm	18,000	3 mm
ILT MR4-188-1	1	1A @ 5V = 5W	12.7 x 12.7 mm	10,000	12.7 mm
ILT MR4E-188	1	1A @ 5V = 5W	12.6 x 16.5 mm	10,000	12.7 mm
Welch Allyn 7103-003	1	0.97A @ 5V = 4.85W	9.5 x 16.5 mm	10,000	12.7 mm
Welch Allyn 7104-003	1	0.97A @ 5V = 4.85W	12.7 x 20.3 mm	10,000	12.7 mm

These lamps produce light by heating the tungsten filament with an electric current. As the filament heats up, it acts as a variable resistance load. The initial cold filament resistance is typically around 10% of the steady-state hot filament resistance. This resistive load can be roughly modeled as shown in [Equation 1](#).

$$R_{lamp} = R_i + \left[(R_f - R_i) \left(1 - e^{-\frac{t}{\tau}} \right) \right] \quad (1)$$

where R_i represents the initial resistance value, R_f represents the final resistance value, and τ represents the time constant to heat up. For the DLP NIRscan Nano ILT 1088-1 lamp, the warm up response is shown in [Figure 4](#). In this figure, $R_i \approx 5.71 \Omega$, $R_f \approx 35.71 \Omega$, $\tau \approx 400$ msec. To account for lot to lot variations, lamp warm-up, and lamp driver startup, the DLP NIRscan Nano assumes a 625 msec delay after enabling the lamps and starting a scan. On initial turn on, the cold filament is at a very low resistance and can allow a very high peak current that is 10x or more than the rated current. This initial in-rush current can reduce the lamp lifetime and affect lamp reliability. This initial in-rush of current is shown in [Figure 4](#). A current limit of $[9800 * 1.18 \text{ V} / 20 \text{ k}\Omega] = 578 \text{ mA}$ is programmed into the lamp driver (OPA567) to limit in-rush current to about 2x the rated continuous current and prolong lamp life. The current limit is set through a 20 k Ω pull-down on the ISET pin of the OPA567.

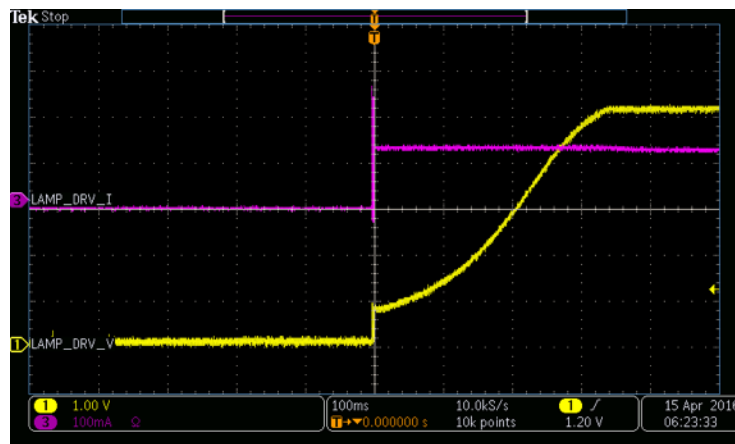


Figure 4. Startup Response of ILT 1088-1 Lamp in DLP NIRscan Nano

Any ripple on the lamp supply will exhibit a variation in light intensity at the detector. Due to the scanning nature of a TI DLP technology-based spectrometer, variations in light intensity during the scan of wavelengths will affect the overall SNR of the system. Therefore, it is necessary to wait for the lamp to warm-up and reach steady-state conditions before starting a scan. This warm-up time varies by lamp type and lamp driver circuitry. The photodetector can be utilized to measure the lamp warm-up time by capturing the light intensity during power-up. Moreover, as the lamp ages, the light intensity decreases. A photodetector under the DLP NIRscan Nano provides lamp intensity readings with each scan to measure lamp degradation. These lamp intensity readings can be used to normalize the scans of a system as the lamp ages.

Figure 5 depicts the DLP NIRscan Nano lamp driver. The difference amplifier (INA213) measures the current across the 100 mΩ sense resistor and amplifies this difference by 50. For two lamps with 140 mA current ($140 \text{ mA} + 140 \text{ mA} = 280 \text{ mA}$), the output of the INA213 is $[50 * 0.1 \Omega * (280 \text{ mA})] = 1.4 \text{ V}$. The OPA567 compares the divided down voltage of the 5 V supply $= 5 \text{ V} * [3.9 \text{ k}\Omega / (10 \text{ k}\Omega + 3.9 \text{ k}\Omega)] = 1.4 \text{ V}$ with the output of INA213. This 5V supply can be driven by a high precision reference voltage device like a REF5050 series for the highest SNR at a slightly increased cost to the system. The INA213 directs the OPA567 to supply current to the lamp if the current across the sense resistor is less than 280 mA. A 20 Ω compensation resistance in the feedback network of the OPA567 prevents oscillations. The INA213 tends to drive the OPA567 past the maximum current since it has a 80 kHz bandwidth while the OPA567 has a 1.2 MHz bandwidth. To minimize this effect, a high pass filter of 10 μF in the OPA567 feedback network passes these high frequency components back to the negative input instead of being analyzed by the INA213.

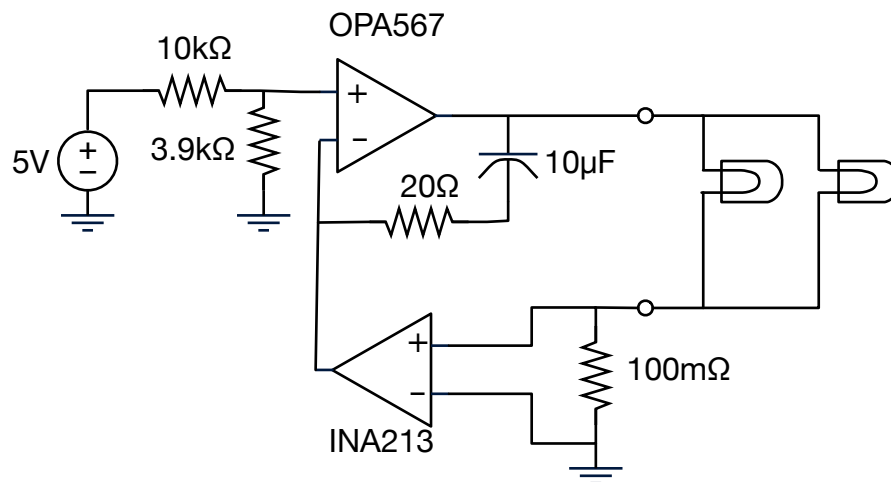


Figure 5. DLP NIRscan Nano Lamp Driver

Replacing the DLP NIRscan Nano lamps with one of the options in Table 1 might require changes to the lamp driver circuit in one or more of the following areas:

- Current shunt monitor (INA21x), if greater than 50 gain is needed
- Feedback resistor and capacitor, if different compensation is needed
- Current limit to OPA567, if greater current is needed
- Voltage divider, if the gain from the current monitor produces a different voltage

For example, using four ILT 1088-1 lamps would require $140 \text{ mA} * 4 = 560 \text{ mA}$ of current. The output of the INA213 is $[50 * 0.1 \Omega * 560 \text{ mA}] = 2.8 \text{ V}$. Thus, the voltage divider into the OPA567 must be changed to a combination of 14 kΩ and 11 kΩ. Also the ISET of the OPA567 pull down must be changed to 12 kΩ to limit the current to under 964 mA.

Figure 6 depicts the DLP NIRscan lamp driver. Since the DLP NIRscan is not a portable battery-powered system like the DLP NIRscan Nano, the larger and higher power consuming OPA569 replaces OPA567. The OPA569 compares the divided down voltage of the 5 V supply = $5 \text{ V} * [30 \text{ k}\Omega / (10 \text{ }\Omega + 30 \text{ k}\Omega)] = 3.75 \text{ V}$ with the output of the INA213. Note that the 5V supply can be driven by a high precision reference voltage device like a REF5050 series for the highest SNR at a slightly increased cost to the system. The output of the INA213 is $[50 * 0.1 \text{ }\Omega * 750 \text{ mA}] = 3.75 \text{ V}$. Thus, the INA213 directs the OPA569 to supply current to the lamp if the current across the sense resistor is less than 750 mA. This driver does not need the feedback compensation of the DLP NIRscan Nano.

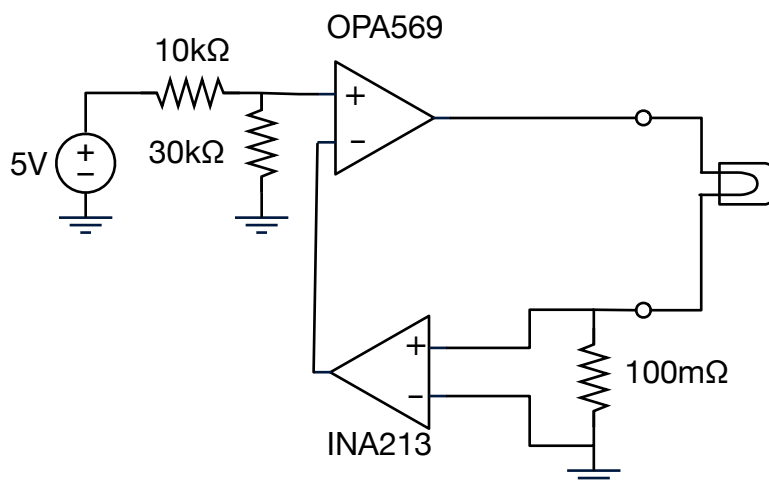


Figure 6. DLP NIRscan Lamp Driver

3.2 Slit Width

The input slit specifications affect both the ability to couple light into the spectrometer as well as its spectral resolution. The slit width should be chosen to create an image width at the DMD corresponding to a desired spectral resolution, while the slit length should be large enough to illuminate the full extent of the DMD panel, maximizing the system's light throughput. Narrowing the slit width increases the spectral resolution of the system, but requires a higher performance optical system to sharply image the smaller slit to the DMD. Refer to [Texas Instruments DLP NIRscan Nano Evaluation Module \(EVM\) Optical Design Considerations](#) for more information on key optical parameters and their interdependence on system performance and size. Narrowing the slit reduces the SNR of the device since less light can be collected from the sample. Refer to [Flexible Trade-offs in Maximizing SNR and Resolution in TI DLP technology-based Spectrometer Systems](#) for more detail on the impact of slit width to SNR and resolution.

3.3 DMD Array Size, Scan Mode, and Pattern Width

DMD array size determines the maximum light collection area and the resolution of the system. The resolution of the system is dependent on the wavelength spectrum that is spread across one dimension of the DMD (for example, width), the slit width, and the DMD pattern width. The other dimension of the DMD (for example, height) and the optical transfer function of the system determine the amount of light collected. The DMD pattern width sets the digital resolution of the system by defining the number of patterns displayed during a scan. The number of patterns corresponds to the number of wavelength points captured across the spectral range. Decreasing the DMD pattern width leads to an increase in the digital resolution with an oversampling of the spectrum at the expense of less light into the photodetector, and thus lower SNR. For best results, select a DMD pattern width so that the digital resolution is at least twice the desired full width half maximum (FWHM). For example, for a 15 nm FWHM between 900 and 1700 nm, use $2 * (1700 - 900) / 15 \geq 107$ wavelength points. Refer to [Flexible Trade-offs in Maximizing SNR and Resolution in TI DLP technology-based Spectrometer Systems](#) for more detail on the impact of DMD pattern width to SNR and resolution.

3.4 Photodetector

For near-infrared (NIR) spectroscopy between 780 and 2500 nm, an InGaAs photodiode is the preferred photodetector due to its high quantum efficiency and responsivity, particularly in the wavelength range of 1100 – 2500 nm. Typical silicon photodiodes are only sensitive up to 1100 nm and are thus not suitable for NIR spectroscopy beyond 1100 nm. In comparison, several types of InGaAs photodiodes cover the wavelength spectrum between 900 - 2500 nm:

- Standard non-cooled InGaAs photodiodes with a wavelength spectrum between 900 and 1700 nm.
- Enhanced non-cooled InGaAs photodiodes with extended sensitivity to wavelengths between 900 – 1900 nm, 900 – 2100 nm, or 900 – 2600 nm.
- Standard cooled InGaAs photodiodes with a wavelength spectrum between 900 and 1670 nm.
- Enhanced cooled InGaAs photodiodes with extended sensitivity to wavelengths between 900 – 1870 nm, 900 – 2070 nm, or 900 – 2570 nm.

Cooled photodiodes include a thermoelectric cooler and temperature sensor for low noise readings. This thermoelectric cooler needs to be driven by an external thermoelectric cooler driver circuit that monitors the photodiode temperature. No single photodiode can efficiently cover the wide spectrum from 780 to 2500 nm. Systems requiring this large coverage would need a combination of silicon and InGaAs photodiodes.

These photodiodes have the equivalent circuit shown in [Figure 7](#). The equivalent circuit consists of a light dependent current source (I_d), a shunt resistance (R_{sh}), junction capacitance (C_j), and a series resistance (R_s).

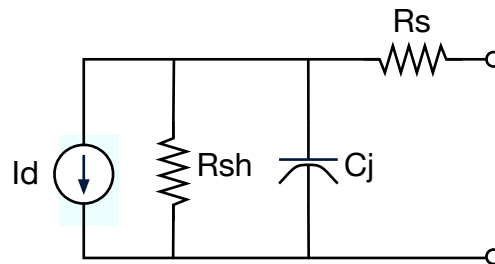


Figure 7. Photodetector Equivalent Circuit

Typically, the photodiode produces a very small current signal, but the signal will be proportional to its photosensitive area. A large photosensitive area produces more current in response to light, at the expense of higher terminal capacitance. The higher capacitance will result in slower response to light, or lower bandwidth. This capacitance will also affect the feedback capacitive compensation of the transimpedance amplifier. The photodiode also has a noise component when current is generated with no incident light. This noise component is typically referred as dark current. Thus, photodiode selection is a tradeoff between cost, wavelength range, photosensitivity, detectivity, capacitance, and dark current. [Table 2](#) and [Table 3](#) show examples of the typical characteristics of Hamamatsu 1 mm and 2 mm photodiodes, respectively. The photodiodes with "A" in the last letter of the part number are photodiodes whose window have anti-reflective coating optimized for the 1550 nm peak. The photodiodes with "K" in the last letter or the part number do not have an anti-reflective coating. As seen in these tables, cooled photodiodes have the least amount of dark current, while large area detectors have greater capacitance. Enhanced detectors offer greater wavelength spectrum range at the expense of greater dark current and capacitance.

Table 2. Hamamatsu 1mm InGaAs Non-cooled Photodetector Characteristics

Part Number	Spectral Range (nm)	Photosensitivity (A/W)	Detectivity (cm ² Hz ^{1/2} /W)	Capacitance (pF)	Dark Current (nA)
G12180-010A	900 – 1700	1.1	6.3 x 10 ¹²	55	0.8
G12181-010K	900 – 1900	1.1	1 x 10 ¹²	230	10
G12182-010K	900 – 2100	1.2	3.5 x 10 ¹¹	230	100
G12183-010K	900 – 2600	1.3	9 x 10 ¹⁰	500	3000

Table 3. Hamamatsu 2mm InGaAs Photodetector Characteristics

Part Number	Cooling	Spectral Range (nm)	Photosensitivity (A/W)	Detectivity (cm ² Hz ^{1/2} /W)	Capacitance (pF)	Dark Current (nA)
G12180-020A	Non-cooled	900 – 1700	1.1	6.3 × 10 ¹²	250	1.5
G12180-120A	One-stage TE-cooled	900 – 1670	1.1	4.4 × 10 ¹³	250	0.1
G12181-020K	Non-cooled	900 – 1900	1.1	1 × 10 ¹²	1000	50
G12181-120K	One-stage TE-cooled	900 – 1870	1.1	5.5 × 10 ¹²	900	5
G12182-020K	Non-cooled	900 – 2100	1.2	3.5 × 10 ¹¹	1000	500
G12182-120K	One-stage TE-cooled	900 – 2070	1.2	1.5 × 10 ¹²	900	50
G12183-020K	Non-cooled	900 – 2600	1.3	9 × 10 ¹⁰	1800	10000
G12183-120K	One-stage TE-cooled	900 – 2570	1.3	3 × 10 ¹¹	1500	3000

The DLP NIRscan and DLP NIRscan Nano supports two scan modes: Column and Hadamard Scans. Column Scan directs a single wavelength of light to the photodetector. Hadamard Scans direct multiple combinations of wavelengths of light to the photodetector. Individual wavelengths are then retrieved through a decoding procedure. Hadamard Scans have the advantage of directing greater signal to the detector over a Column scan. As example, the DLP NIRscan Nano system collects the following optical power and current output for Column and Hadamard Scans with Reflective and Transmissive illumination heads:

- Reflective Illumination
 - Column Scan: (35 nW) (1.1 A/W) = 38.5 nA
 - Hadamard Scan: (510 nW) (1.1 A/W) = 560 nA
- Transmissive Illumination
 - Column Scan: (525 nW) (1.1 A/W) = 577 nA
 - Hadamard Scan: (9 μW) (1.1 A/W) = 9.9 μA

Note that the Hamamatsu GS12180-010A is linear up to 8 mW of optical power. The extended range photodiodes (supporting a spectral range past 1700 nm) are linear up to 2-4 mW of optical power.

3.4.1 Thermo-electric Cooler

Some photodetectors have a built-in thermo-electric cooler (TEC) to lower the dark noise. [Figure 8](#) shows a typical TEC driver. This driver utilizes the INA330 precision amplifier to measure the thermistor from the photodiode and drive the OPA569 up to a pre-set current limit when cooling is needed. The INA330 measures the difference in currents between the thermistor input (Rt) and the precision resistor (Rs) inputs of the INA330. The difference is used to determine when to drive the OPA569 to cool the photodiode. This TEC driver circuit is used in the DLP NIRscan.

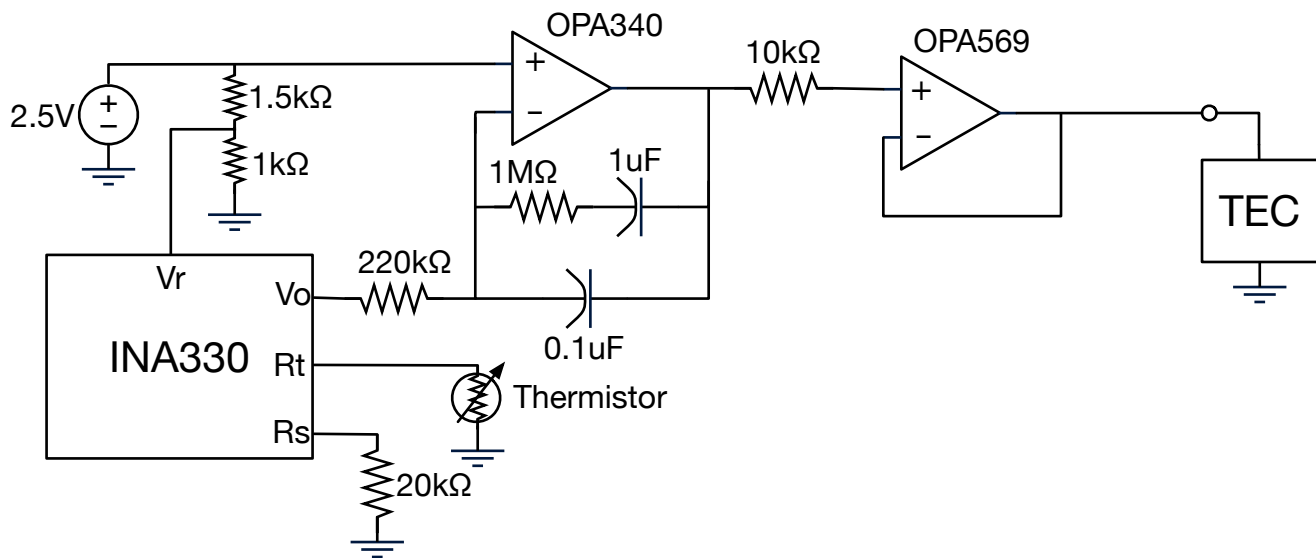


Figure 8. DLP NIRscan TEC Driver

3.5 Amplification

InGaAs photodiodes generate a small amount of current when a photon impacts the P-N junction of the semiconductor. The following architectures amplify and digitize the small current of the photodiode:

- Transimpedance amplifier through discrete components or an integrated photodiode and amplifier. This architecture converts the photodiode current into a voltage and then digitizes the voltage with an ADC. The voltage is typically oversampled by the ADC to average out the noise.
- Charge integration through discrete components or a charge digitizing ADC. This architecture utilizes capacitors for charge accumulation and then convert this charge into a digital value. The converted digital value is dependent on the integration time.

The transimpedance amplifier converts the small photodiode current into a voltage. This conversion requires analog filters and analog gain to raise the signal from the noise floor. The amplified voltage of the photodiode is then digitized with an ADC. The transimpedance amplifier architecture is best suited for photodiodes that produce higher input currents, achieve wide analog bandwidth, offer high flexibility with simple changes of feedback elements, and handle high speed conversion. On the other hand, the charge digitizing ADC is a single device that optimizes the analog front end with the ADC to provide good system performance for low level inputs at the expense of flexibility, bandwidth, and speed of conversion. The integrated photodiode and amplifier falls in between the discrete transimpedance amplifier and the charge digitizing ADC in terms of flexibility, bandwidth, and speed of conversion. For flexibility, bandwidth, speed, and the larger signals produced by the large area photodiodes in conjunction with the Hadamard scans of a DLP system, the transimpedance amplifier architecture is better suited for a DLP technology-based spectrometer. For this reason, this application note covers only a transimpedance amplifier architecture. Nevertheless, [Table 7](#) compares the charge digitizing ADC (DDC112) with the other ADCs used with transimpedance amplifiers. Note that in charge integration architectures, the signal level increases with integration time and requires adjustments to the gain factor to prevent ADC saturation. Alternatively, transimpedance amplifier architectures have constant signal level, and oversampling the voltage averages out the noise. The design of the transimpedance amplifier architecture requires the voltage range to match the ADC dynamic range.

3.5.1 Transimpedance Amplifier

A single stage transimpedance amplifier implementation of the analog signal chain is shown in Figure 9. It is composed of the photodetector, a single stage transimpedance amplifier, analog-to-digital converter in differential mode, and the required reference voltages, V_r . The analog inputs of the ADC in differential mode provides greater noise immunity by coupling the noise into both inverting and non-inverting inputs of the ADC, thus cancelling common mode noise and improving its SNR. The differential mode also splits the gain of the system across two transimpedance amplifiers to maximize the bandwidth of the amplifiers.

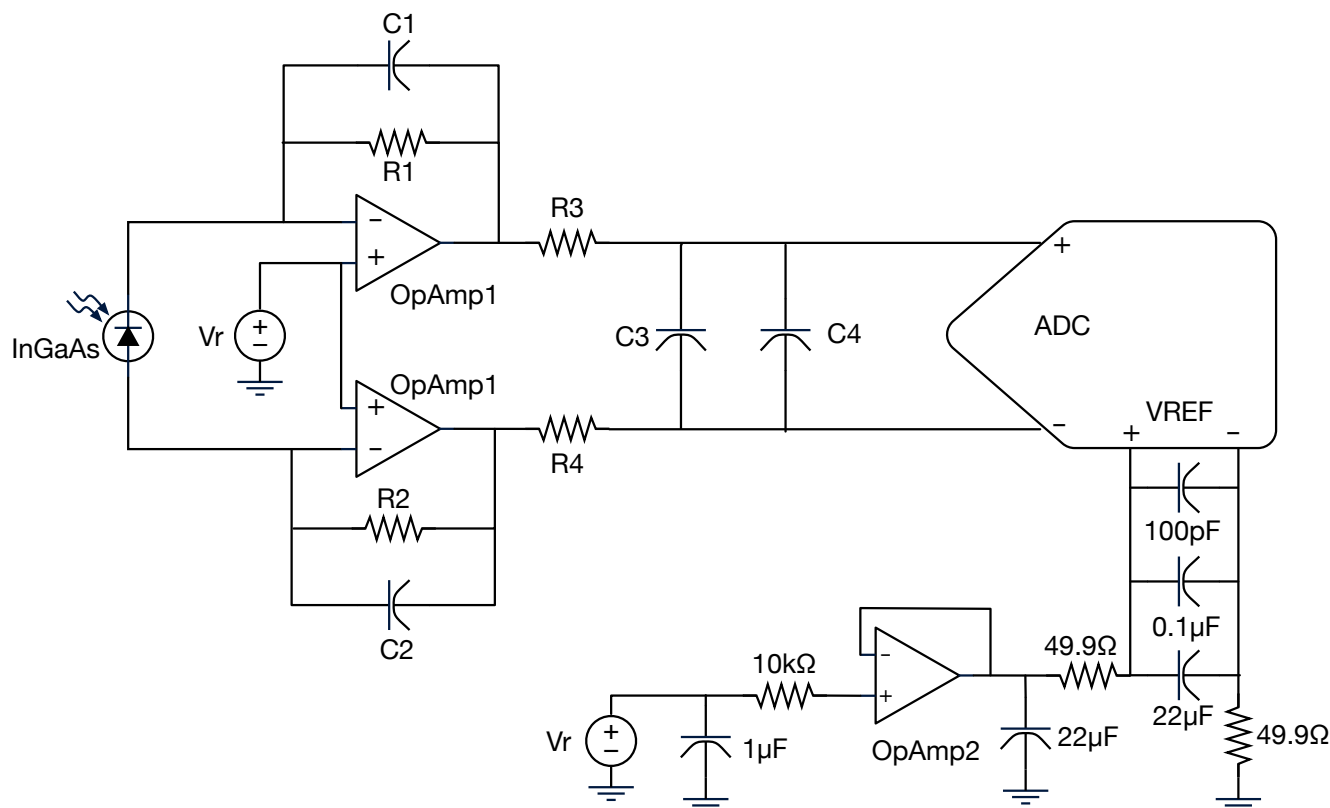


Figure 9. Detector Analog Signal Chain

The maximum gain of the transimpedance amplifier determines the signal bandwidth. If this gain is set too high, the attainable bandwidth of the signal spectrum is limited. If this gain is set too low, then the low signal degrades the SNR of the system. Thus, careful selection of this gain is needed. The transimpedance amplifier circuit with the photodiode equivalent circuit are shown in Figure 7. This signal chain is used in the [TINA-TI™ SPICE-Based Analog Simulation Program](#) to analyze this circuit's DC, transient, and frequency domain performance.

3.5.1.1 Transimpedance Gain

The gain of a single transimpedance amplifier is given by the feedback and series resistance. Typical InGaAs photodiodes have very small series resistance, so this gain can be written as shown in [Equation 2](#).

$$Gain_{TIA} = R_f \quad (2)$$

Note that the differential mode implementation of the transimpedance amplifier doubles the gain for the system as shown in [Equation 3](#).

$$Gain_{system} = 2R_f \quad (3)$$

For this equivalent transimpedance amplifier circuit of the analog signal chain, the total gain is given by twice the feedback resistor, $Gain = 2R_f$. The maximum signal into the ADC is twice the reference voltage, $2V_r$. Hence, the maximum gain is the ratio between the largest photodetector signal and the maximum signal into the ADC as shown in [Equation 4](#):

$$\text{Max Gain} = 2V_r / \text{Max}(I_D) = 2R_f, \text{ so } R_f = V_r / \text{Max}(I_D) \quad (4)$$

In the DLP NIRscan Nano, utilizing a reflective illumination with a Hadamard scan corresponds to $R_f = 2.5 \text{ V} / 10.5 \mu\text{A} \approx 240 \text{ k}\Omega$. The feedback resistor and circuit of [Figure 9](#) was modeled with TINA-TI and provides 112.5 dB of gain with the following parameters:

- Hamamatsu InGaAs G12181-010A photodiode
- OpAmp1 = OpAmp2 = OPA2376
- C1 = C2 = 51 pF
- R1 = R2 = 240 k Ω
- R3 = R4 = 301 Ω
- C3 = 47 nF and C4 = 100 pF
- ADS1255 with input buffer off

On the other hand, the DLP NIRscan provides 93.6 dB of gain with the following parameters:

- Hamamatsu InGaAs G12183-120K photodiode
- OpAmp1 = OpAmp2 = OPA2376
- C1 = C2 = 1000 pF
- R1 = R2 = 24 k Ω
- R3 = R4 = 301 Ω
- C3 = 0.1 μF and C4 = 100 pF
- ADS1255 with input buffer off

3.5.1.2 Bandwidth Considerations

The bandwidth is a function of the source capacitance, the feedback capacitance, and the gain-bandwidth product of the amplifier used. The source capacitance (C_S) is the sum of the photodiode capacitance (C_J), the common-mode capacitance of the amplifier (C_{CM}), the differential capacitance of the amplifier (C_{DIFF}), and board parasitic capacitance (C_{PAR}).

$$C_S = C_J + C_{CM} + C_{DIFF} + C_{PAR} \quad (5)$$

For the amplifier selection, the transimpedance amplifier bandwidth (f) is inversely proportional to the square root of the gain bandwidth product (GBWP) divided by the product of the feedback resistor and source capacitance as shown in Equation 6. For an in-depth explanation, refer to the application reports ([Texas Instruments Compensate Transimpedance Amplifiers Intuitively](#)) and ([Transimpedance Considerations for High-Speed Amplifiers](#)).

$$f = \sqrt{\frac{GBWP}{2\pi R_f C_S}} \quad (6)$$

Note that most OpAmp data sheets specify typical GBWP. To account for process variations, use 60% of the typical value in Equation 7. This equation indicates that if very large gain is needed in the transimpedance amplifier, a two-stage amplifier architecture might be recommended. The first stage provides moderate gain in the transimpedance state and is followed by a second broadband gain stage.

To compensate for the photodetector capacitance in the feedback path and stabilize the circuit, an external capacitor is placed across the feedback resistor. The optimal value of this capacitor is given by Equation 7 as shown in [Texas Instruments Compensate Transimpedance Amplifiers Intuitively](#).

$$C_f \geq \frac{1}{4\pi R_f GBWP} \left[1 + \sqrt{1 + 8\pi R_f C_S GBWP} \right] \quad (7)$$

Increasing the value of the feedback capacitor, C_f , trades bandwidth for stability. Also, larger feedback capacitors filter out the high-frequency component of the photodetector signal. Some experimentation may be needed to account for all parasitic capacitances, environmental variations, and the large varying capacitance range of photodetectors.

3.5.1.3 Noise Immunity

For noise immunity, a differential signal is employed by the transimpedance amplifier and the ADC.

3.6 Analog to Digital Signal Conversion

For best results, an extremely low-noise, high linearity, high resolution analog to digital converter minimizes the noise added by the conversion. To optimize the digital resolution of the system, the dynamic range and reference voltages of the ADC must be matched with the maximum photodetector signal.

3.6.1 Dynamic Range and Voltage Reference

In a TI DLP technology-based spectrometer, the programmable nature of the patterns on the DMD can vary the amount of light incident on the photodetector. For Hadamard Scans, up to half of the micromirrors direct light to the photodetector. For Column Scans, a small fraction of the micromirrors direct light to the photodetector. This large dynamic range must be mapped into the input voltage range of the ADC. Depending on the illumination head and materials scanned, the typical ADC bit resolution ranges from 16-bits to 24-bits.

Using a 24-bit ADC in differential mode, the ADC's input voltage range is given by the difference of the differential inputs: (AIN+ – AIN-). Internal to the ADC, this range is mapped to the difference between its voltage reference inputs: (VREF+ – VREF-). For this detector signal chain architecture, VREF- is set to ground, and VREF+ is set to the reference voltage (V_r), leading to the following full scale voltage levels and bit codes:

- $(\text{AIN+} - \text{AIN-}) \leq 2V_r$
- $\text{Code} = 2^{24}(\text{AIN+} - \text{AIN-})/[2V_r] = 2^{23}(\text{AIN+} - \text{AIN-})/V_r$

3.6.2 Voltage Reference

For the best measurement resolution, careful selection of the voltage reference, V_r , avoids unused ADC codes and matches the dynamic range of the photodetector to the allowed input voltage range of the ADC. For example, [Table 4](#) shows the DLP NIRscan Nano ADC signal values at 10 nm resolution with a transimpedance amplifier with 112.5 dB gain and 2.5 V reference voltage: REF5025.

Table 4. DLP NIRscan Nano Typical Detector Signal at 10 nm Resolution Scan ($V_r = 2.5\text{V}$)

Illumination Type	Scan Type	Converted Detector Signal at ADC	Maximum Bit Depth
Reflective	Column	~ 30,000	15
	Hadamard	~ 450,000	18
Transmissive	Column	~460,000	19
	Hadamard	~7,930,000	23

[Table 4](#) demonstrates that this configuration is sufficient to support the broad range of inputs from reflective and transmissive illumination modules. However, for the end application that only requires a reflective illumination module, the dynamic range of the ADC is underutilized. [Table 4](#) shows that the maximum reflective signal only consumes 18-bits, with the upper 6-bits not used. In this case, the system's resolution can be further optimized by utilizing a 1V voltage reference: LM4140. With $V_r = 1\text{V}$, this reference reduces the maximum analog input ($\text{AIN+} - \text{AIN-}$) = $2V_r$ from 5V to 2V. [Table 5](#) shows the maximum values with $V_r = 1\text{V}$. For reflective scans, this table shows two to three more bits of precision depending on the scan type. The entry highlighted in red shows that for a transmissive Hadamard scan, the 1V reference overflows the 24-bit ADC. Hence, a 1V reference is recommended for all reflective illumination, as well as for transmissive illumination with highly absorbent samples.

Table 5. DLP NIRscan Nano Typical Detector Signal for 10nm Resolution Scan ($V_r = 1\text{V}$)

Illumination Type	Scan Type	Converted Detector Signal at ADC	Maximum Bit Depth
Reflective	Column	~ 72,000	17
	Hadamard	~ 1,080,000	21
Transmissive	Column	~1,104,000	21
	Hadamard	~19,032,000	25

3.6.3 ADC Programmable Gain Amplifier

Depending on the light absorption of the object being scanned, large differences in light collected at the photodiode will result in smaller input signals at the ADC, decreasing the measurement resolution. Refer to [Table 6](#) for typical maximum signal levels at ADC for 1V and 2.5V reference voltages. For optimal mapping of the ADC resolution to the input signal, the programmable gain amplifier (PGA) of the ADS1255 is used during scans. The ADS1255 supports a low noise PGA with 2x, 4x, 8x, 16x, 32x and 64x. During a scan, a quick scan is initially performed to determine the peak input signal at the ADC. Then, the PGA is automatically set by the DLP NIRscan Nano firmware to the maximum value that does not overflow the ADC inputs.

Table 6. DLP NIRscan Nano Typical Maximum ADC Input Voltage with PGA Setting

PGA Setting	ADC Maximum Input Voltage ($V_r = 2.5V$)	ADC Maximum Input Voltage ($V_r = 1V$)
1	5.00 V	2.00 V
2	2.50 V	1.00 V
4	1.25 V	0.50 V
8	0.625 V	0.25 V
16	312.5 mV	125 mV
32	156.25 mV	62.5 mV
64	78.125 mV	31.25 mV

3.6.4 Sampling Frequency

Depending on the material sampled and the amount of light reaching the photodetector, the sampling frequency can vary. The DLP controllers in the DLP NIRscan (DLPC350) and DLP NIRscan Nano (DLPC150) can load binary patterns on the DMD at up to 2880 Hz. Each pattern presents a single column or an element of a Hadamard scan. During each scan, the photodetector is sampled 5-20 times to average out the noise. This results in typical sampling rates of 15 to 60 kHz.

3.6.5 Analog to Digital Converter

[Table 7](#) shows several options for analog to digital converters available from Texas Instruments. Highlighted in yellow is the ADS1255 used in the DLP NIRscan and DLP NIRscan Nano. Depending on the application and the amount of light reflected by the material, select an ADC with a bit resolution that meets the dynamic range of the system and offers sufficient noise free bits. Then select a sampling rate that allows several measurements per wavelength to average out the noise. For improved noise immunity, use differential input mode by utilizing 2 channels in differential mode or one single differential channel. These ADCs include programmable digital filters that optimize the bit depth resolution and the desired data sampling rates.

Configurable software options of the programmable gain amplifier (PGA) and analog front end (AFE) gain provide more flexibility for data capture. Some ADCs have integrated AFEs that replace the transimpedance amplifier circuit shown in [Figure 9](#). For example, the AFE44xx devices have software configurable transimpedance amplifiers but operate at lower sampling rates. The AFE4490 also averages four conversions in the 5 kHz sampling rate providing an effective 20 kHz sample rate.

Charge digitizing ADC or analog integrators, such as the DDC112, allow direct connection of the photodetector to its input, avoiding the need for a transimpedance amplifier circuit. The DDC112 uses internal and external integrating capacitors to convert the photodiode current to voltage in continuous mode. These devices do not support the fast sampling rates nor the fine tuneability of the integrated AFE44xx devices.

Table 7. ADC Options From Texas Instruments for TI DLP Technology-based Spectrometers

Part Number	Channels	Resolution (bits)	Sample Rate (kHz)	PGA (Multiplier)	Analog Front End
ADS1271	1 differential	24	105	-	-
ADS1255	2	24	30	1, 2, 4, 8, 16, 32, 64	-
ADS1292	2	24	8	1, 2, 4, 8, 12	-
ADS1250	2	20	25	1, 2, 4, 8	-
ADS8887	1 differential	18	100	-	-
ADS8867	1 differential	16	100	-	-
ADS1192	2	16	8	1, 2, 4, 8, 12	-
AFE4490	1 differential	22	5	1, 1.5, 2, 3, 4	TIA with $R_f = 10k - 1M$ and $C_f = 5 - 250pF$
AFE4405	1 differential	24	1	-	TIA with $R_f = 10k - 2M$ and $C_f = 2.5 - 25pF$
DDC112	2	20	3	-	Internal and external integrating capacitors. Direct connection to photodiode.

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