Texas Instruments DLP® NIRscan™ Nano Evaluation Module (EVM) Optical Design Considerations

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ABSTRACT

TI DLP® technology offers unique benefits and functionality to spectrometer design. For a comparison of DLP spectroscopy to existing technologies see *Texas Instruments DLP Technology for Spectroscopy* (DLPA048). The optical design of a DLP spectrometer involves interactions between many interdependent parameters. Modification of individual components often requires the simultaneous alteration of numerous other elements in order to maintain desired performance levels. This application report identifies the key optical parameters, and discusses their interdependent impact on system size and performance. The design choices for the DLP NIRscan™ Nano EVM are explained, and from these, generally applicable design guidelines are derived.

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1   System Layout

The NIRscan Nano EVM system layout is shown in Figure 1. During typical use, the sample under test is pressed against the sapphire window and illuminated by two broadband tungsten filament lamps. Light diffusely reflected by the sample is gathered by the collection lens and focused through the slit. The collected light is collimated by the first set of lenses, passes through a longpass filter, and then strikes the diffraction grating which disperses the light into its constituent wavelengths. The longpass filter blocks light with wavelengths shorter than 900 nm from striking the grating. Otherwise, the second diffraction order of this light would overlap with the first order of the 900-nm to 1700-nm wavelength range, reducing the signal-to-noise ratio (SNR) of the system. The focusing lenses then form an image of the slit at the digital micromirror device (DMD), with the different wavelengths spread across the length of the DMD. Sets of DMD mirror columns are turned on in sequence to reflect one wavelength of light at a time to the condenser lenses, which concentrates this energy onto the single point InGaAs detector. Table 1 displays the primary design specifications of the NIRscan Nano EVM.
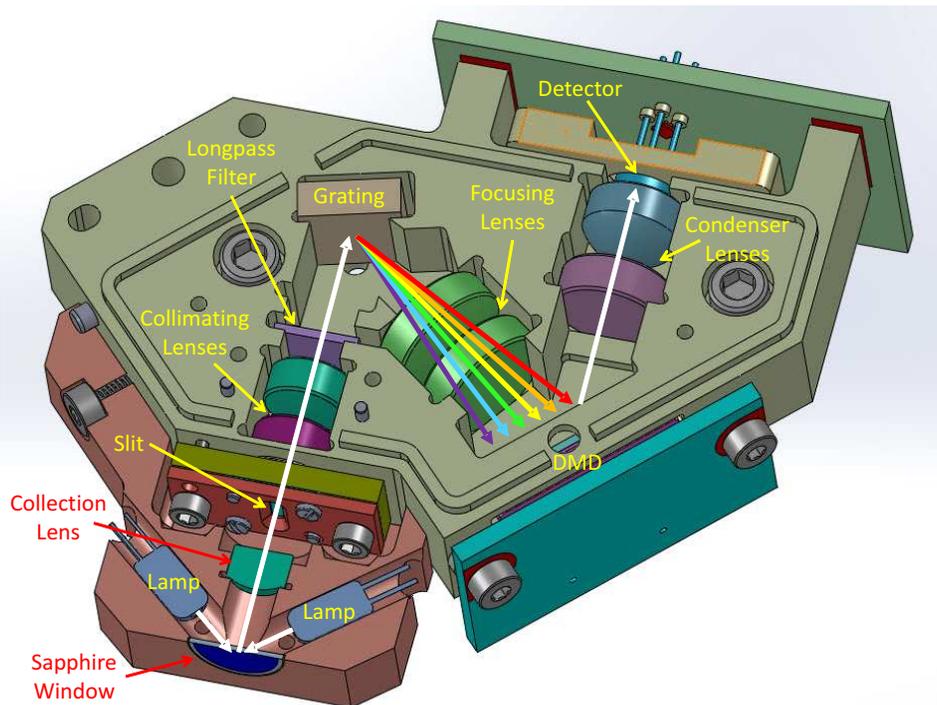
Figure 1. NIRscan Nano EVM With Cover Removed

Table 1. NIRscan Nano EVM Design Specifications

PARAMETER	DESIGN VALUE
Slit ƒ-number	2.5
Slit dimensions	1.8 × 0.025 mm
DMD	DLP2010NIR
DMD ƒ-number	3.8
Spectral range	900 to 1700 nm
Spectral resolution	10 nm
Detector diameter	1 mm
Detector type	Uncooled InGaAs
Optical engine dimensions	33 × 29 ×10 mm

2   Illumination Module

The NIRscan Nano EVM is equipped with a removable diffuse reflectance illumination module. This unit operates by illuminating the sample under test at an angle so that specular reflections are not collected, while diffuse reflections are gathered and focused through the slit. Two lens-end, tungsten filament lamps serve as the light source. They are designated as *lens-end* lamps because the front end of the glass bulb is formed into a lens to direct more light from the filament to the sample test region. The collection lens gathers collimated light from a 2.5-mm diameter region at the sample plane. The size of the collection region is matched to the nominal illumination spot size created by the lens-end lamps.

The NIRscan Nano EVM illumination module is designed for the sample to be placed directly against the sapphire window, where the two angled light source paths and the vision cone of the collection lens all intersect. If the sample is shifted farther away from the window, the system may not collect enough light to perform an accurate measurement. If sample contact is not desirable, the illumination module could be redesigned to accommodate non-contact measurements. The position and angle of the lamps could be changed to illuminate a point in space. In such a setup, it is more difficult to prevent stray light, such as room lights, from entering the spectrometer and impacting the accuracy of its measurements.

There are also methods of altering the illumination module to increase the signal strength of the spectrometer input. One approach is to make the module an imaging relay, instead of collecting a collimated bundle of light from the sample. This would increase the collection efficiency at the sample, while simultaneously reducing the size of the sampling region, making non-homogeneous samples difficult to measure accurately.

An alternative solution is to increase the illumination source amplitude by increasing the quantity, power, or size of the lamps. An example of this is the four lamp illumination module shown in Figure 2. Additionally, elliptical reflector housings or focusing lenses could be added to collect more light from each lamp.
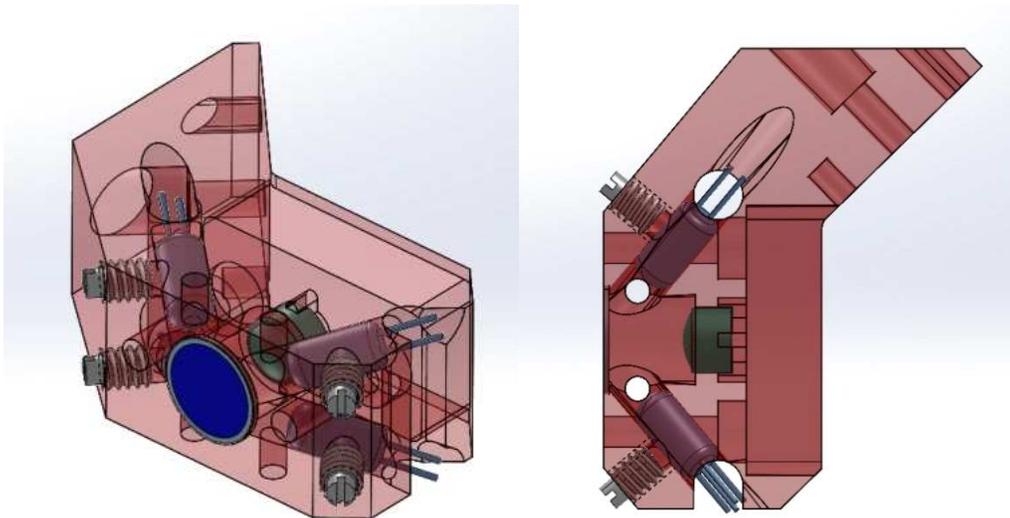

Figure 2. Four Lamp Diffuse Reflectance Illumination Module

3 Fiber Coupled Illumination

Optical fibers are often used to couple different illumination modules with the main spectrometer system. DLP spectrometers will typically have taller entrance slits than array detector systems because the DMD is taller than the array detector. This allows for increased signal throughput, but can make fiber coupling more complex. Standard optical fibers can be utilized, but will only illuminate a small section of the entrance slit, as shown in Figure 3. In order to take advantage of the DLP spectrometer's large etendue, a round-to-linear fiber bundle should be used. These optical fibers have multiple cores arranged in a circular pattern at one end, and a linear configuration at the opposite end. The round end can be utilized at the sample as in typical spectroscopy illumination modules, while the linear end can be more effectively coupled to the slit, as shown in Figure 4.
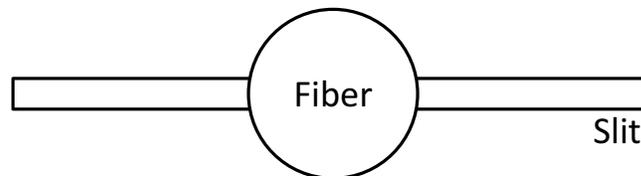

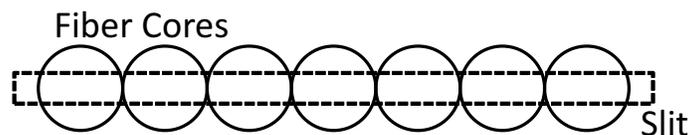
Figure 3. Slit Fill Factor with Standard Fiber

Figure 4. Slit Fill Factor with Round-to-Linear Fiber

Other important considerations for fiber coupling are numerical aperture matching and fiber to slit placement. To maximize fiber coupling efficiency, the numerical aperture (NA) of the fiber output should be no larger than the acceptance NA of the spectrometer system. The NIRscan Nano EVM entrance slit operates at 0.2 NA, which matches many standard optical fibers. The most basic fiber coupling setups place the fiber end directly at the slit entrance with as minimal a gap as possible. Any separation between the fiber and slit rapidly decreases the coupling efficiency. If the fiber cannot be placed at the slit due to mechanical restrictions, it is possible to design an optical relay which images the output of the fiber to the entrance slit plane. Such a module could replace the standard diffuse reflectance module on the NIRscan Nano EVM.

4 DMD F-Number

While the DLP2010NIR DMD accepts up to an f/1.7 cone angle, the NIRscan Nano EVM operates at f/3.8 at the DMD. This slower f-number offers a compromise between light throughput and engine complexity. Faster f-numbers allow the spectrometer to collect more light from the sample and increase the diffraction efficiency of the DMD, ultimately resulting in a higher SNR. The tradeoff for these advances comes in terms of optical engine size and complexity. The lenses must increase in size in order to accommodate the larger light cone. Operating at a faster f-number may cause a degradation of the optical image quality at the DMD plane unless additional lenses or aspheric lens surfaces are added. Any resulting decrease in the slit image quality at the DMD will reduce the spectral resolution of the device. Faster f-numbers may also necessitate total internal reflectance (TIR) or reverse total internal reflectance (RTIR) prism arrangements at the DMD in order to separate the incoming and outgoing light bundles.

5 DMD Illumination Angle

The DLP2010NIR device is typically illuminated at a 34° angle of incidence, resulting in the reflected light leaving normal to the DMD. However, the dispersive properties of the diffraction grating and lens elements cause the dispersed slit image to form along a tilted plane not perpendicular to the optical axis. The tilt angle of this plane will vary widely between different designs and may not match the desired 34° angle of incidence. For instance, the NIRscan Nano EVM design creates the dispersed slit image at a 10° angle. The image plane angle can be adjusted by the addition of a wedge prism element, or by tilting and decentering the focusing lenses between the grating and DMD.

Instead of altering the 10° image plane angle, the NIRscan Nano EVM accommodates it by reversing the DMD illumination path, as shown in Figure 5. The moderately slow ƒ-number at the DMD, in conjunction with the shallow angle of incidence, allow the incident and reflected light to remain within the angular usage range over which the DLP2010NIR DMD was designed. This means the DMD window aperture will not obstruct the light path. The 17° pixel tilt of this device also aids in separating the incident and reflected light cones. This allows the lenses to be placed closer to the DMD without any mechanical interference, keeping the system more compact.
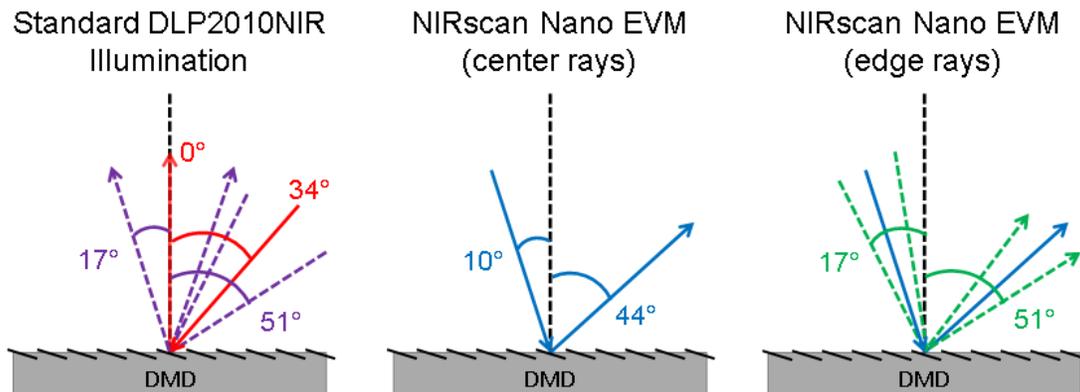

Figure 5. NIRscan Nano EVM DMD Illumination Angles

When reversing the DMD illumination path it is also important to consider the off-state light. The DLP2010NIR DMD utilizes perpendicular tilt directions for on-state and off-state pixels. This architecture directs off-state light away from the main optical path, even when using a reverse illumination scheme, where it can be blocked by proper chassis and baffle design.

This configuration illuminates the DMD mirrors from an angle opposite their on-state tilt direction, which increases the gap between adjacent mirrors from the perspective of the incoming illumination. More light will therefore be absorbed underneath the mirrors, instead of reflected on towards the detector. It is important to take this into consideration when estimating total system efficiency to ensure the final design meets SNR and measurement performance goals.

6   Slit Parameters

The input slit parameters impact the SNR and spectral resolution capabilities of the system. The NIRscan Nano EVM possesses an ƒ/2.5 acceptance cone at the slit because this matches many standard fiber optic bundles, allowing for easier coupling with fiber illumination modules. The ratio between slit and DMD ƒ-number sets the magnification of the system, which is 1.52 for the NIRscan Nano EVM. Knowing the system magnification, one can then determine an appropriate slit width and length. The slit width should be chosen to create an image width at the DMD corresponding to a desired spectral resolution, while the 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 while simultaneously reducing the SNR since less light can be collected from the sample under test. The optical system must be capable of sharply imaging the smaller slit to the DMD in order to realize this gain in spectral resolution.

7   Spectral Resolution

The spectral resolution of the NIRscan Nano EVM is defined as the spectral full width at half maximum (FWHM) of a measurement taken using an input source with zero spectral width. This can be modeled in optical design software by filling the input slit with a monochromatic light source and measuring the resultant FHWM of the image at the DMD plane. This method of analysis shows that the NIRscan Nano EVM achieves a 10-nm spectral resolution with its 25-μm wide slit. Thinner slits could be used to achieve finer resolution at the cost of SNR. It is also important to consider the resolution of the DMD to ensure it can adequately sample the spectral image of the slit. The FHWM of a monochromatic slit image in the NIRscan Nano EVM subtends nine DMD pixels, ensuring this is not an issue.

8   Diffraction Grating

Diffraction grating selection influences the system size and layout. A tighter groove spacing (increased grooves per mm) will increase the divergence angle variation between different wavelengths. This separates the broad spectrum light over a shorter distance, allowing the DMD to be positioned closer to the grating and still capture the entire spectral range. Increasing the grating frequency also degrades the optical image quality at the DMD, increasing the difficulty of the optical engine design. Varying the groove spacing allows one to balance the system size and optical performance.

Another important consideration is how the dispersed spectrum fills the DMD array. Typically, the DMD is underfilled in the dispersion axis, and overfilled in the orthogonal axis, to allow for image location shifts caused by optical and mechanical tolerances. For a more in-depth explanation of these effects, see *Texas Instruments DLP Spectrometer Design Considerations* (DLPA049).

9   Condenser and Detector

The condenser lenses serve to collect the light from any DMD mirrors in the on-state and concentrate it onto the single point detector. The smaller the region that all wavelengths are condensed into, the smaller the detector that can be used. Shrinking the detector size has two main benefits - decreasing the cost, and increasing the SNR. In order to accomplish this, the condenser should operate at a fast f-number to create a greatly de-magnified image of the DMD at the detector plane. This portion of the system is optimized to improve collection efficiency and energy distribution uniformity at the detector over imaging performance. The NIRscan Nano EVM employs purposeful defocus at this image plane by shifting the detector position towards the condenser lenses. The detector is placed where the light bundle is most narrow to balance the amount of light collected across all wavelengths.

10   Optical Lens Elements

Lens material selection plays an important role in the optical design. All the NIRscan Nano EVM lenses are made of Ohara S-LAM66 and have only spherical and flat surfaces. This glass is relatively common and inexpensive, while still having a high index of refraction and physical properties conducive to standard manufacturing techniques. The total lens count could be reduced through the use of aspheric optics made of a lower index moldable glass. This approach could help to reduce the size of the system and the complexity of the mechanical chassis. However, molding custom aspheric glass lenses is only viable in terms of cost at large manufacturing quantities. Plastic lens materials are not suitable due to absorption bands within the 900-nm to 1700-nm range.

11   Stray Light

Stray light refers to errant signals caused by incorrectly classifying the wavelength of a signal. This causes erroneous spectrum measurement output, and limits the linearity of absorbance units (AU) that can be accurately measured. For an in-depth treatise on potential stray light sources, refer to *Texas Instruments DLP Spectrometer Design Considerations* (DLPA049).

12   Opto-Mechanics

It is important to consider mechanical alignment tolerances when performing the optical design. Slit and detector position may be actively aligned to compensate for tolerance errors and increase system performance. For further information on opto-mechanical design considerations, refer to *Texas Instruments DLP Spectrometer Design Considerations* (DLPA049).

13   Modifying the NIRscan Nano EVM

Due to the interdependent nature of the system's optical design parameters, only a few are well-suited to customization. Replacing the illumination module or entrance slit offers an effective path for adapting the spectrometer to different applications. The number, type, and arrangement of lamps can be altered to increase the light output or accommodate different sample positions, as shown in Section 2. A transmissive or fiber coupled illumination module could be used instead of the standard diffuse reflectance setup. More details on fiber coupled illumination can be found in Section 3. Adjusting the width of the entrance slit allows resolution and SNR to be traded off against each other, as shown in Section 7. The single point photodetector could also be exchanged with another as long as it still fits within the mechanical housing constraints.

Modifications to the illumination module, entrance slit, and detector of the NIRscan Nano EVM can be performed without any changes to the core system. More extensive alterations such as shifting the spectral measurement band or adjusting the spectral resolution further than exchanging the entrance slit is capable of will require redesigning the entire optical path and mechanical chassis. The NIRscan Nano EVM design files serve as a reference and starting point for such endeavors.

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