Application Note

DMD Optical Efficiency for Visible Wavelengths

TEXAS INSTRUMENTS

ABSTRACT

The purpose of this document is to summarize the optical properties that are most important in estimating the efficiency of a Digital Micromirror Device (DMD) in a projection system.

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1 Purpose and Scope

The next three sections discuss the fill factor, window optical properties, and the active mirror array properties, respectively. This report concludes with a discussion on calculating the overall efficiency.

As discussed in more detail in Section 6, overall optical efficiency can be estimated using Equation 1.

$$Efficiency_{DMD} = transmission_{window} \times efficiency_{fillfactor} \times efficiency_{diffraction} \times reflectivity_{mirror} \times transmission_{window} \quad (1)$$

where

- $transmission_{window}$ is single-pass window transmission including two anti-reflection surfaces. This term is accounted for twice because light travels through the window twice.
- $efficiency_{fillfactor}$ is the fractional mirror coverage (on-state mirrors) as viewed from the illumination direction
- $efficiency_{diffraction}$ is the mirror array diffraction efficiency which can include effects of non-flat mirrors
- $reflectivity_{mirror}$ is the mirror reflectivity including mirror scatter

Overall DMD efficiency is generally a product of fill factor, window transmission, diffraction efficiency, and mirror reflectivity, which are described in more detail in the following sections.

1.1 Limitations

This document does not include system-level efficiency losses such as etendue mismatches, which can be better assessed using a ray trace model based on the actual optical design. Factors that affect contrast ratio are also important, however, the interactions are often much more complex requiring rigorous electromagnetic scattering theory of the optical system, and it would be difficult to summarize all these factors in this type of report.

1.2 Acronyms Used in This Document

Abbreviations	Descriptions
DMD	Digital Micromirror Device
AOI	Angle of Incidence
WLP	Wafer Level Package

2 On-State Fill Factor

Table 2-1 shows typical on-state fill factor based on DMD micromirror pitch.

- Tilt angle - Nominal mirror tilt angle is listed. Each DMD data sheet specifies the actual tilt angle and how much it can vary.
- Fill factor - The mirror array constitutes discrete micro-mirrors with a given mirror pitch. Fill factor is defined as the percentage of light reflected by the on-state mirrors when illuminated by a beam of light incident at 2x the mirror tilt angle with the assumption of 100% mirror reflectivity. For the actual mirror reflectivity, see Section 5. The mirror pitch, structure and tilt angle are directly related to the fill factor value. Geometrical ray trace simulation methods are used to calculate fill factor for DMD arrays.

Table 2-1. DMD On-State Fill Factor

DMD Examples (1)	MICROMIRROR Pitch (µm)	Nominal Tilt Angle (deg.)	Illumination *f*-number	Typical On-State Fill Factor (2) (3)
DLP7000	13.68	12	2.4	**92%**
DLP650LE	10.8	12	2.4	**92%**
DLP780TE DLP800RE	9.0	14.5	2.0	**97%**
DLP3030-Q1 DLP5534-Q1 DLP4501 DLP9000	7.6 7.6 7.56 7.56	12	2.4	**94%**
DLP3010	5.4	17	1.7	**93%**

(1) DMD example list is not comprehensive and many other devices may be available within each micromirror pitch category.
(2) On state fill factor values are approximate. Refer to DMD data sheet for device-specific values.
(3) The on state fill factors are calculated using illumination at the native *f*-number corresponding to the tilt nominal angle.
  a. 12° tilt = *f*/2.4
  b. 14.5° tilt = *f*/2.0
  c. 17° tilt = *f*/1.7

3 Window Properties

The two main types of DMD windows are directly related to the packaging types:

- Type A DMD packaging uses Corning 7056 glass (typically about 3 mm thick).
- Wafer Level Packaging (WLP, often referred to as Sxxx package) uses Corning Eagle XG glass (typically about 1 mm thick or less).

Both the WLP window and the Type A window have an anti-reflective thin film coating to reduce reflections and increase transmission efficiency. Depending on the application, either the visible, UV, or NIR coating is used.

The values below describe a **single pass of visible light (420 nm–680 nm)** with random polarization through the window, and accounting for two surface coatings.

- Average transmittance, T_{ave} ≥ 99% at all angles 0–30° AOI,
- Average transmittance, T_{ave} ≥ 97% at all angles 30–45° AOI

All transmittance values are the total transmittance of the window (through both surfaces and glass). A transmission number of 96% is used in the Table 6-1 calculation representing a double pass through the window with approximately 99% transmission at each coated surface. See the DMD data sheets for device specific values.

For more information on window transmittance, see *Wavelength Transmittance Considerations for DLP® DMD Window*.

4 Mirror Diffraction Efficiency

4.1 Mirror Flatness

The semiconductor processing required to build the mirror structure can result in the mirrors deviating from a perfectly flat plane. However, the processing is designed and controlled to minimize the non-flatness or non-planarity of the mirror. Diffraction modeling described below can be used to predict losses due to non-flat mirrors. However, the calculation below assume a flat mirror.

4.2 Mirror Diffraction Efficiency

The active array area consists of a large rectangular array of aluminum-based mirrors which can tilt to one of two stable angles. For the 13.68 µm, 10.8 µm, and 7.6/7.56 µm micromirror pixel sizes, this is typically +12° and –12° around the diagonal. The 9.0 µm micromirror pixel size also tilts around the diagonal at typically +14.5° and –14.5°. The 5.4 µm micromirror pixels are different in that they tilt approximately 17° about the orthogonal direction.

The illumination and projection *f*-numbers are typically matched to obtain the tradeoff of efficiency and contrast ratio. However, even under these conditions, there is some loss of light due to clipping of the diffracted light at the projection lens aperture stop. Because the size of the mirrors is not large with respect to the wavelength, the mirror reflected light diffracts into a larger cone angle which results in a loss of light.

The longer wavelengths (red) are diffracted more than shorter wavelengths (blue), resulting in diffraction efficiency that typically decreases at longer wavelengths.

In order to more accurately model the complex diffraction pattern that arises, use the fact that the array of tilted mirrors behaves similarly to a classic blazed optical diffraction grating. Conceptually, the best way to approach broadband source diffraction is to consider it as a combination of a large number of plane waves varying in wavelength and direction. All of these plane wave sources can be combined incoherently to assess the final diffraction pattern.

For a two-dimensional array of mirrors illuminated by a single wavelength, collimated laser beam, the far field appears as an array of bright points (diffraction orders) that are spaced approximately by *λ/pitch* in angle, where *λ* is the wavelength. Scalar diffraction theory that can be approximated using the fast Fourier transform algorithm (FFT) can generally be used for this calculation with reasonably good accuracy. The amplitude of the array of bright points is modulated by the far-field pattern of an individual mirror which is generally close to a sin(x)/x shape. The far-field radiance function can be calculated as a function of direction cosines *α* and *β* using the Fourier transform as described in Equation 2.

$$L'(\alpha, \beta - \beta_o) = K \gamma_o \frac{\lambda^2}{A_s} \left| \mathrm{F} \left\{ U_o(\hat{x}, \hat{y}; 0) \exp(i 2\pi \beta_o \hat{y}) \right\} \right|^2 \quad \text{for} \quad \alpha^2 + \beta^2 \leq 1$$
$$L'(\alpha, \beta - \beta_o) = 0 \quad \text{for} \quad \alpha^2 + \beta^2 \geq 1 \tag{2}$$

Here, the quantity $U_0(\hat{x}, \hat{y}; 0)$ represents the EM field (magnitude and phase) as it leaves the surface of the DMD mirror array. The calculated radiance profile, $L(\alpha, \beta - \beta_0)$, can then be mathematically truncated corresponding to the acceptance angle defined by the projection lens aperture. By integrating the radiance over incident angle and wavelength and keeping track of the power inside the aperture relative to the total power, you can calculate the diffraction efficiency.

The resulting far-field radiance pattern for a white-light incoherent source has radiating arms of alternating color as shown in Figure 4-1. The energy in the outer arms is lost as only the central part of the beam is collected by the projection lens. The calculated diffraction efficiency varies with mirror pitch, mirror tilt, and wavelength.

Because the far-field diffraction pattern (or image at the projection pupil) depends upon illumination angle, mirror pitch, mirror tilt angle, and wavelength, the far-field diffraction from white light has a significant amount of color variation. The most important factors in determining diffraction-induced color variation are mirror pitch and mirror tilt angle, the illumination angle being less of a factor. This color variation causes the diffraction efficiency to vary approximately as a sinusoid as a function of wavelength as shown in Figure 4-3 through Figure 4-7. A spectral plot of diffraction efficiency shows periodic oscillations in wavelength, and the period of those oscillations generally depends on the pitch of the mirrors—the smaller pitch mirrors showing a longer period. As a result, the diffraction efficiency can change significantly as a function of wavelength. Also, variation in tilt angle across the DMD mirror array and from device to device causes the spectral peaks to shift in wavelength.

Figure 4-2 shows the calculated nominal diffraction efficiency for the various pixel types as a function of pixel pitch. As expected, there is a general reduction in diffraction efficiency as the pixel is scaled down in pitch.

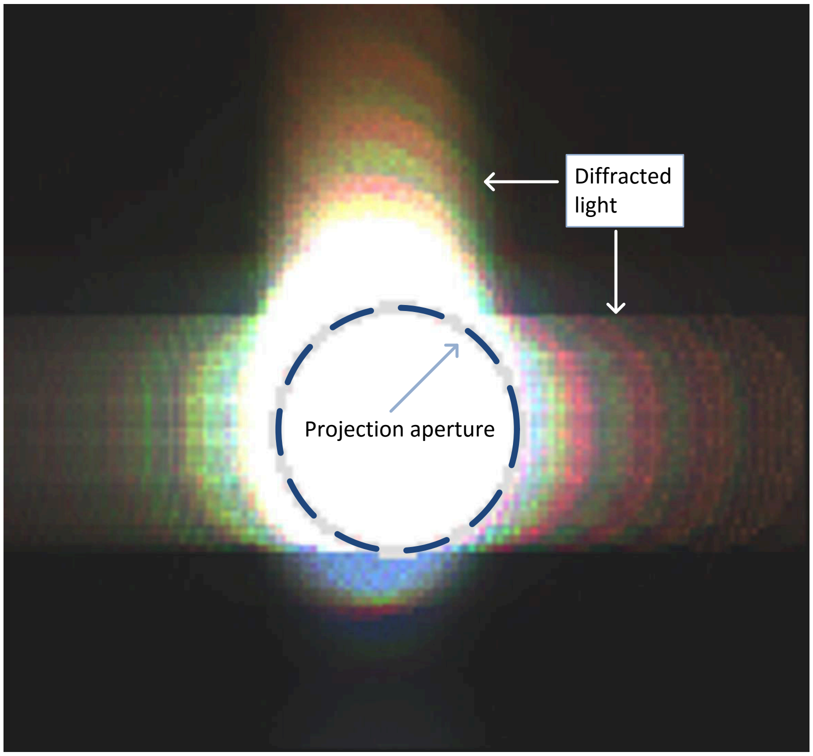

Figure 4-1. Simulated 5.4 µm Pitch DMD Far Field Radiance Image; Dashed Circle Shows Outline of Projection Lens Aperture Edge

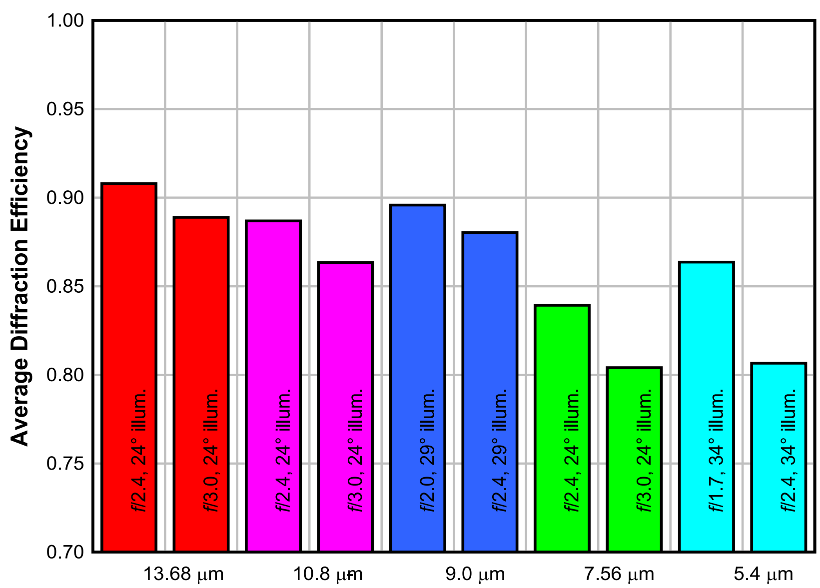

Figure 4-2. Summary of Calculated Average Photopic Diffraction Efficiencies for Different Pixel Sizes (420 nm–680 nm wavelength)

Figure 4-3 through Figure 4-7 show the spectral diffraction efficiencies for different *f*-numbers matched between illumination and projection, and nominal design tilt angles.

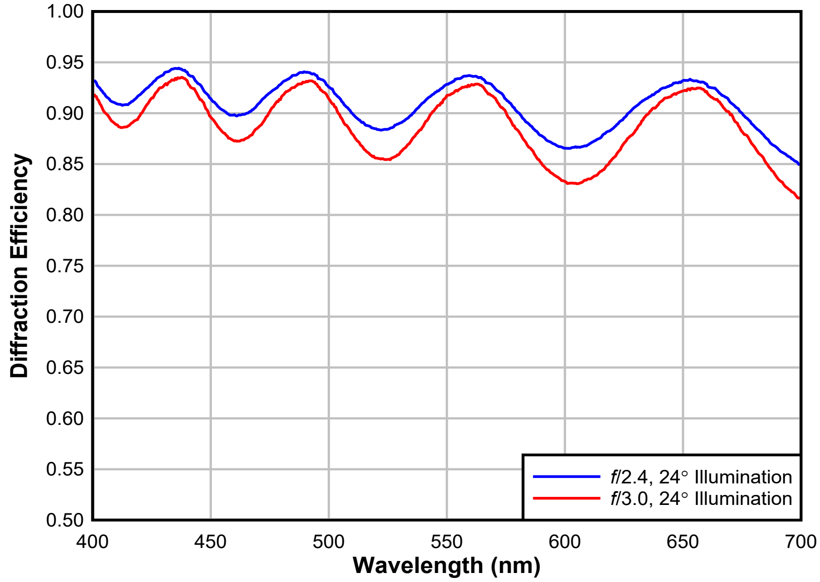

Figure 4-3. 13.68 µm Pitch DMD Mirror Calculated Diffraction Efficiency (matched illumination and projection *f*-numbers)

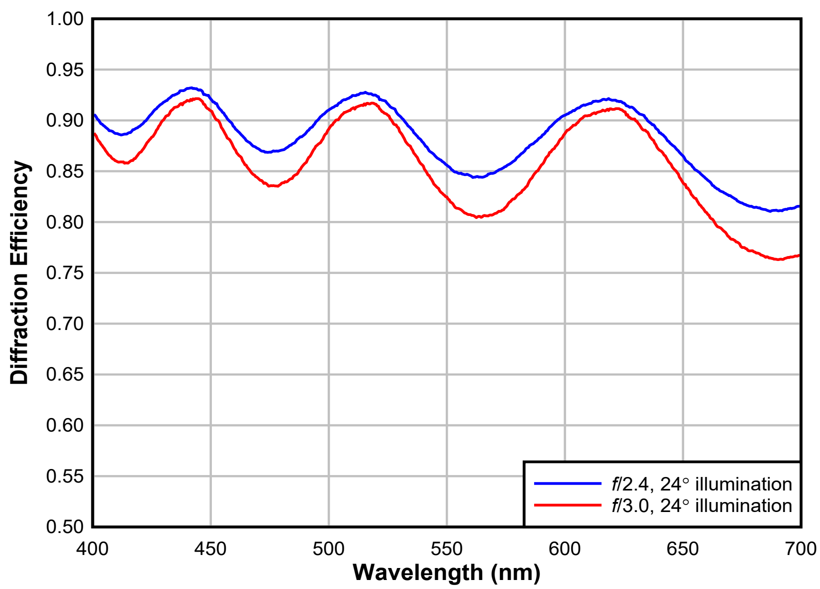

Figure 4-4. 10.8 µm Pitch DMD Mirror Calculated Diffraction Efficiency (matched illumination and projection *f*-numbers)

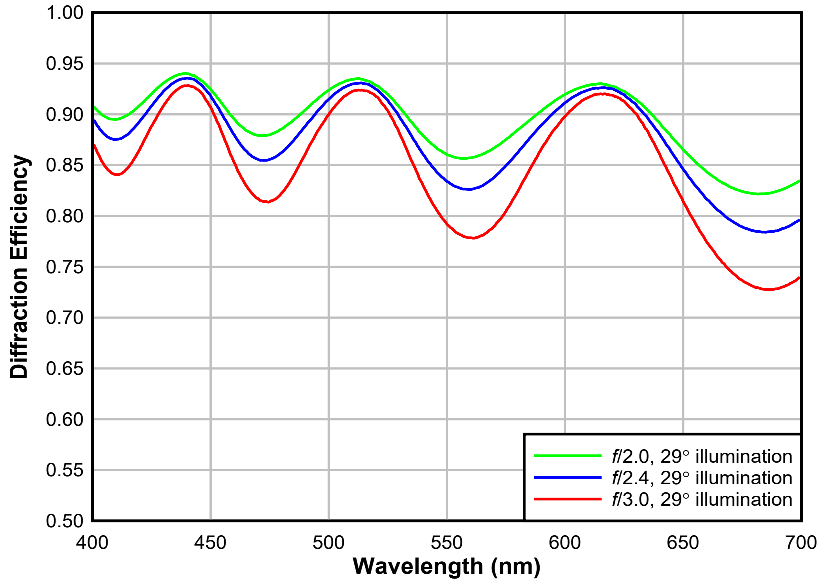

Figure 4-5. 9.0 µm Pitch DMD Mirror Calculated Diffraction Efficiency (matched illumination and projection *f*-numbers)

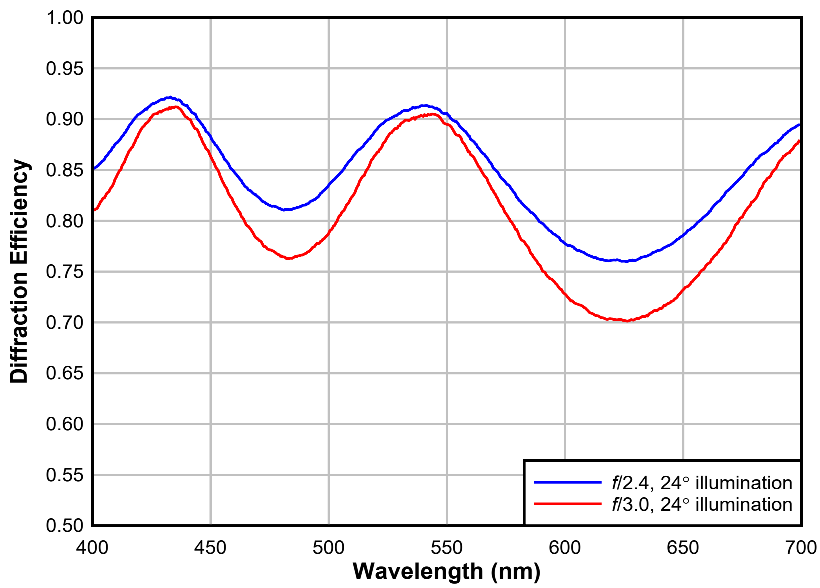

Figure 4-6. 7.56 µm Pitch DMD Mirror Calculated Diffraction Efficiency (matched illumination and projection *f*-numbers)

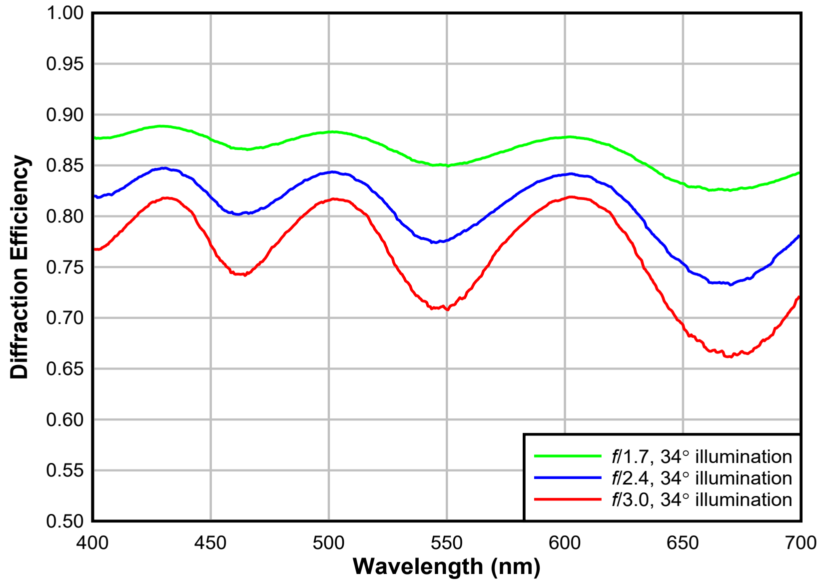

Figure 4-7. 5.4 µm Pitch DMD Mirror Calculated Diffraction Efficiency (matched illumination and projection *f*-numbers)

4.3 Diffraction Efficiency with Mismatched Illumination and Projection *f*-numbers

The mismatched *f*-number approach is a method to improve diffraction efficiency performance. By utilizing a slower illumination *f*-number (larger *f*-number) and faster projection *f*-number (smaller *f*-number), the diffraction efficiency increases because more of the diffracted light from the reflected illumination beam is collected into the projection lens aperture. An example case is a system with the 7.56 µm pitch DMD, *f*/3 illumination and *f*/2.4 projection optics as shown in Figure 4-8. The matched *f*/2.4 illumination and *f*/2.4 projection case has an average diffraction efficiency of 83.9% while the mismatched *f*/3 illumination and *f*/2.4 projection case has an average diffraction efficiency of 90.5%. This method works across DMD devices. The margin of improvement depends largely on the selected *f*-numbers and DMD mirror size being used.

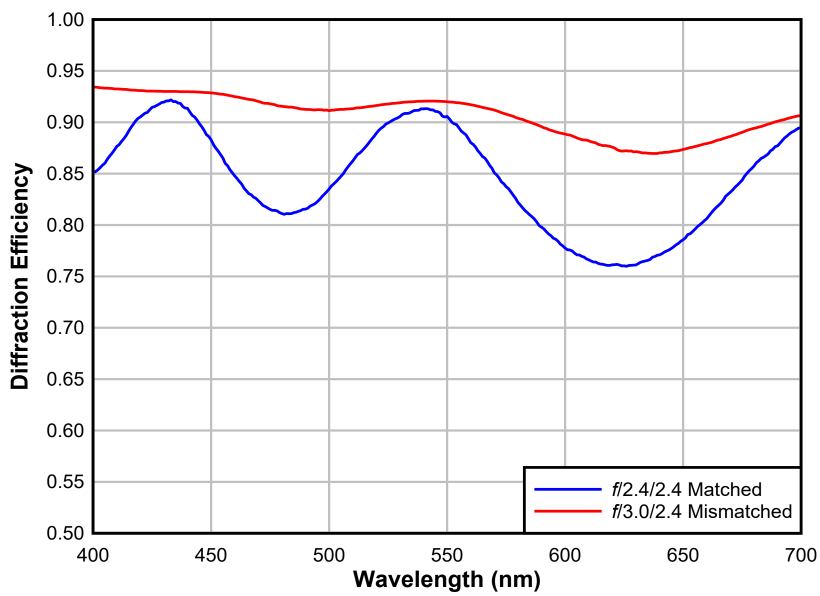

Figure 4-8. 7.56 µm Pitch DMD Mirror Calculated Diffraction Efficiency With Matched and Mismatched *f*-numbers

A direct laser system, where larger illumination *f*-numbers (smaller illumination system etendue) does not significantly lower the projector luminous output, benefits from the mismatched *f*-number technique. In a slower *f*-number system with matched illumination and projection *f*-number, the local minima for a given diffraction efficiency curve is lower as compared to a faster, matched *f*-number system. This reduced diffraction efficiency can be greatly improved by utilizing the mismatched *f*-number technique, driving the diffraction efficiency much higher than a matched *f*-number system would provide. The mismatching of *f*-number in this way flattens or reduce the peak to valley difference in the diffraction efficiency curves.

The mismatched *f*-number technique trades off some system contrast for diffraction efficiency. The system contrast lies between the lower matched *f*-number and the higher matched *f*-number of those of the projection and illumination path. For example, for a mismatched *f*-number system in which the illumination is *f*/3 and projection is *f*/2.4, the contrast is higher than a *f*/2.4 matched projection system and lower than a *f*/3 matched projection system built around the same DMD.

5 Mirror Reflectivity

The active array area consists of a large rectangular array of aluminum based mirrors. The mirrors are nominally 89% reflective in the visible range (420 to 680 nm).

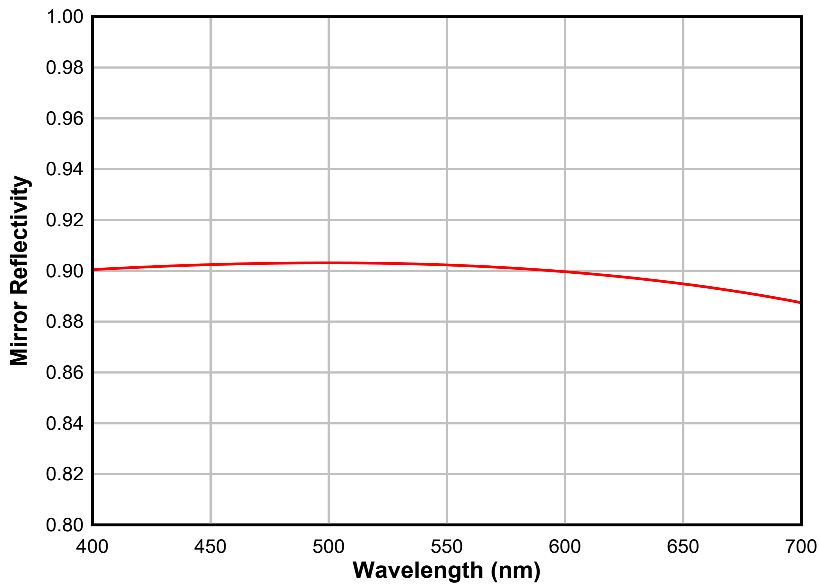

Figure 5-1. DMD Mirror Typical Reflectivity

6 Estimating Overall DMD Efficiency

Overall optical efficiency can be estimated using Equation 3.

$$Efficiency_{DMD} = transmission_{window} \times efficiency_{fillfactor} \times efficiency_{diffraction} \times reflectivity_{mirror} \times transmission_{window} \quad (3)$$

where

- $efficiency_{fillfactor}$ is the fractional mirror coverage (on-state mirrors) as viewed from the illumination direction
- $transmission_{window}$ is single-pass window transmission including two anti-reflection surfaces. This term is accounted for twice because light travels through the window twice.
- $efficiency_{diffraction}$ is the mirror array diffraction efficiency which can include effects of non-flat mirrors
- $reflectivity_{mirror}$ is the mirror reflectivity including mirror scatter

The photopic numbers shown in Table 6-1 assume a source with a flat power spectrum with wavelengths of 420 nm–680 nm. More accurate results can be obtained for a given light source by multiplying the spectral diffraction efficiency by the actual source spectrum.

Table 6-1. Total Photopic Average Efficiency Calculation(1)

DMD Pitch (µm)	Tilt Angle (deg)	*f*-number	Diff. Eff.	On-State Fill	Window Transmission (Double Pass)	Mirror Refl.	Total Eff.
13.68	12	2.4	89%	92%	96%	89%	**70%**
10.8	12	2.4	87%	92%	96%	89%	**68%**
9.0	14.5	2.0	89%	97%	96%	89%	**72%**
7.6/7.56	12	2.4	84%	94%	96%	89%	**67%**
5.4	17	1.7	86%	93%	96%	89%	**68%**
5.4	17	2.4	80%	93%	96%	89%	**64%**

(1) The values in this table are approximate. For specific values, see the device-specific DMD data sheet.

7 References

- “Linear systems formulation of non-paraxial scalar diffraction theory” James E. Harvey, Proc. of SPIE Vol. 8122

8 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision A (June 2019) to Revision B (April 2023) **Page**

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