

DMD Optical Efficiency for Visible Wavelengths

Application Report



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1	Purpose and Scope	4
1.1	Purpose and Scope	4
1.2	Limitations	4
2	On-State Fill Factor	5
2.1	On-State Fill Factor	5
3	Window Properties	6
3.1	Window Properties	6
4	Mirror Diffraction Efficiency	7
4.1	Mirror Flatness	7
4.2	Mirror Diffraction Efficiency	7
5	Mirror Reflectivity	14
5.1	Mirror Reflectivity	14
6	Estimating Overall DMD Efficiency	15
6.1	Estimating Overall DMD Efficiency	15
7	Terms and Abbreviations	16
7.1	Terms and Abbreviations	16
8	References	17
8.1	References	17

List of Figures

4-1.	Simulated 5.4 μm Pitch DMD Far Field Radiance Image; Dashed Circle Shows Outline of Projection Lens Aperture Edge	8
4-2.	Summary of Calculated Photopic Diffraction Efficiencies for Different Pixel Sizes (400 nm–700 nm wavelength).....	9
4-3.	13.6 μm Pitch DMD Mirror Calculated Diffraction Efficiency	10
4-4.	10.8 μm Pitch DMD Mirror Calculated Diffraction Efficiency	11
4-5.	7.6 μm Pitch DMD Mirror Calculated Diffraction Efficiency	12
4-6.	5.4 μm Pitch DMD Mirror Calculated Diffraction Efficiency	13

List of Tables

2-1.	DMD On-State Fill Factor	5
6-1.	Total Photopic Efficiency Calculation	15

Purpose and Scope

1.1 Purpose and Scope

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. 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 [Chapter 6](#), overall optical efficiency can be estimated using [Equation 1](#).

$$\text{Efficiency}_{\text{DMD}} = \text{transmission}_{\text{window}} \times \text{efficiency}_{\text{fillfactor}} \times \text{efficiency}_{\text{diffraction}} \times \text{reflectivity}_{\text{mirror}} \times \text{transmission}_{\text{window}}$$

where

- $\text{transmission}_{\text{window}}$ is single-pass window transmission including two anti-reflection surfaces. This term is accounted for twice because light travels through the window twice.
 - $\text{efficiency}_{\text{fillfactor}}$ is the fractional mirror coverage (on-state mirrors) as viewed from the illumination direction
 - $\text{efficiency}_{\text{diffraction}}$ is the mirror array diffraction efficiency which can include effects of non-flat mirrors
 - $\text{reflectivity}_{\text{mirror}}$ is the mirror reflectivity including mirror scatter
- (1)

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.

1.2 Limitations

This document does not include system-level efficiency losses such as etendue mismatches, which can be better assessed using a raytrace 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.

On-State Fill Factor

2.1 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 datasheet specifies the actual tilt angle and how much it can vary.
- Fill Factor - Calculated from viewpoint of nominal illumination angle from DMD die surface. Typically twice the mirror tilt angle (for example, 24 degrees for a 12 degree tilt). These numbers can be calculated using ray tracing, however as the pixel structures get smaller with respect to the wavelength more rigorous methods are required for better accuracy. See Section 4.2 for a description of scalar diffraction methods. More rigorous methods such as Finite Difference Time Domain (FDTD) can be used for even greater accuracy.

Table 2-1. DMD On-State Fill Factor

DMD EXAMPLES ⁽¹⁾	MICROMIRROR PITCH (μm)	TILT ANGLE (deg.)	TYPICAL ON-STATE FILL FACTOR ⁽²⁾
DLP7000	13.6	12	92%
DLP650LE	10.8	12	92%
DLP303X-Q1 DLP553X-Q1 DLP4501 DLP9000	7.6	12	94%
DLP3010	5.4	17	93%

⁽¹⁾ DMD example list is not comprehensive and 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.

Window Properties

3.1 Window Properties

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

- Type A uses Corning 7056 glass (typically about 3 mm thick).
- Wafer Level Packaging (WLP, often referred to as Sxxx package) uses 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 IR 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.

- Minimum transmittance, $T_{\min} \geq 97\%$ at all angles 0–30° AOI,
- Average transmittance, $T_{\text{ave}} \geq 99\%$ at all angles 0–30° AOI,
- Average transmittance, $T_{\text{ave}} \geq 97\%$ 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 [Window Transmittance Considerations for DLP® DMD Window Application Report \(DLPA031\)](#) for more information on window transmittance, .

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. Typically, the mirror is sufficiently flat that light losses in a visible light, F/2.4 projector is less than 1%. This loss is included in the diffraction efficiency calculation.

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 13.6 μm , 10.8 μm , and 7.6 μm micromirror sizes, this is typically +12 and -12 degrees around the diagonal. The 5.4 μm micromirror devices are different in that they tilt approximately 17 degrees 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 clipped more than the shorter wavelengths (blue), resulting in a diffraction efficiency loss that increases for 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) which are spaced approximately by λ/pitch in angle, where λ is the wavelength. Scalar diffraction theory which 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](#).

$$\begin{aligned}
 L'(\alpha, \beta - \beta_o) &= K \gamma_o \frac{\lambda^2}{A_s} \left| \mathbf{F} \left\{ U_o(\hat{x}, \hat{y}; 0) \exp(i2\pi\beta_o \hat{y}) \right\} \right|^2 && \text{for } \alpha^2 + \beta^2 \leq 1 \\
 L'(\alpha, \beta - \beta_o) &= 0 && \text{for } \alpha^2 + \beta^2 \geq 1
 \end{aligned}
 \tag{2}$$

Here, the quantity $U_o(\hat{x}, \hat{y}; 0)$ represents the EM field (magnitude and phase) as it leaves the surface of the DMD mirror array. The calculated radiance profile, $L(\alpha, \beta - \beta_o)$, 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 4-6](#). 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 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 4-3](#) through [Figure 4-6](#) show the spectral diffraction efficiencies for different f-numbers matched between illumination and projection, and nominal design tilt angles. Note that the 13.6 μm , 10.8 μm , and 7.6 μm mirrors land at 12 degrees, while the 5.4 μm mirrors tilt at 17 degrees.

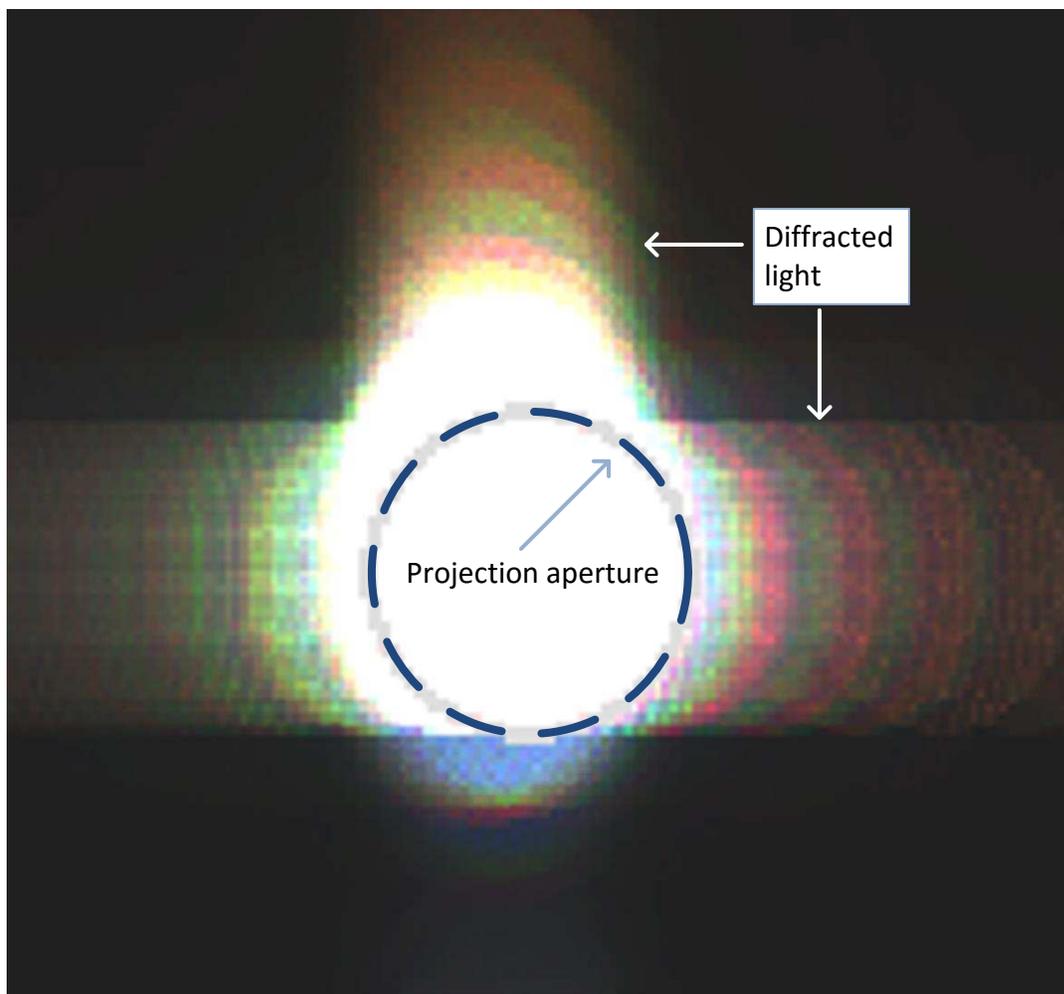


Figure 4-1. Simulated 5.4 μm Pitch DMD Far Field Radiance Image; Dashed Circle Shows Outline of Projection Lens Aperture Edge

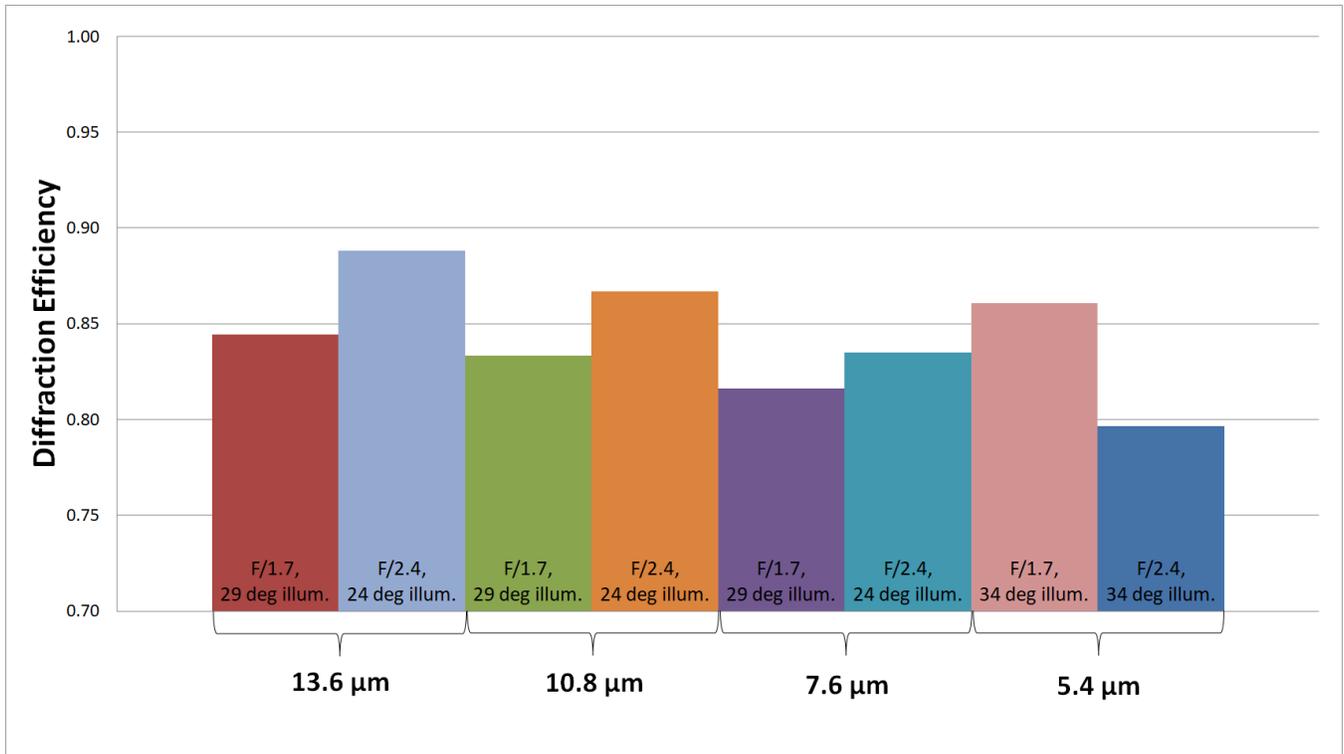


Figure 4-2. Summary of Calculated Photopic Diffraction Efficiencies for Different Pixel Sizes (400 nm–700 nm wavelength)

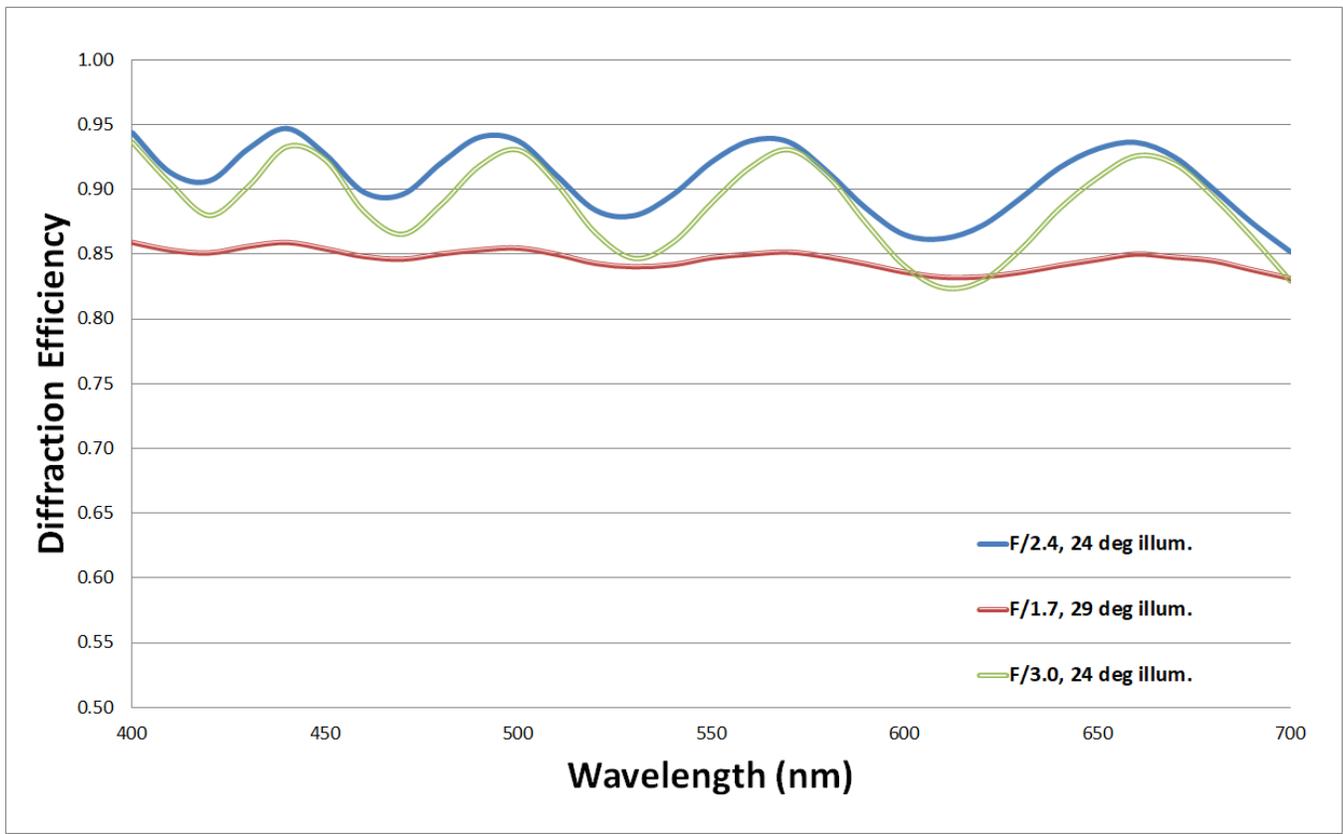


Figure 4-3. 13.6 μm Pitch DMD Mirror Calculated Diffraction Efficiency

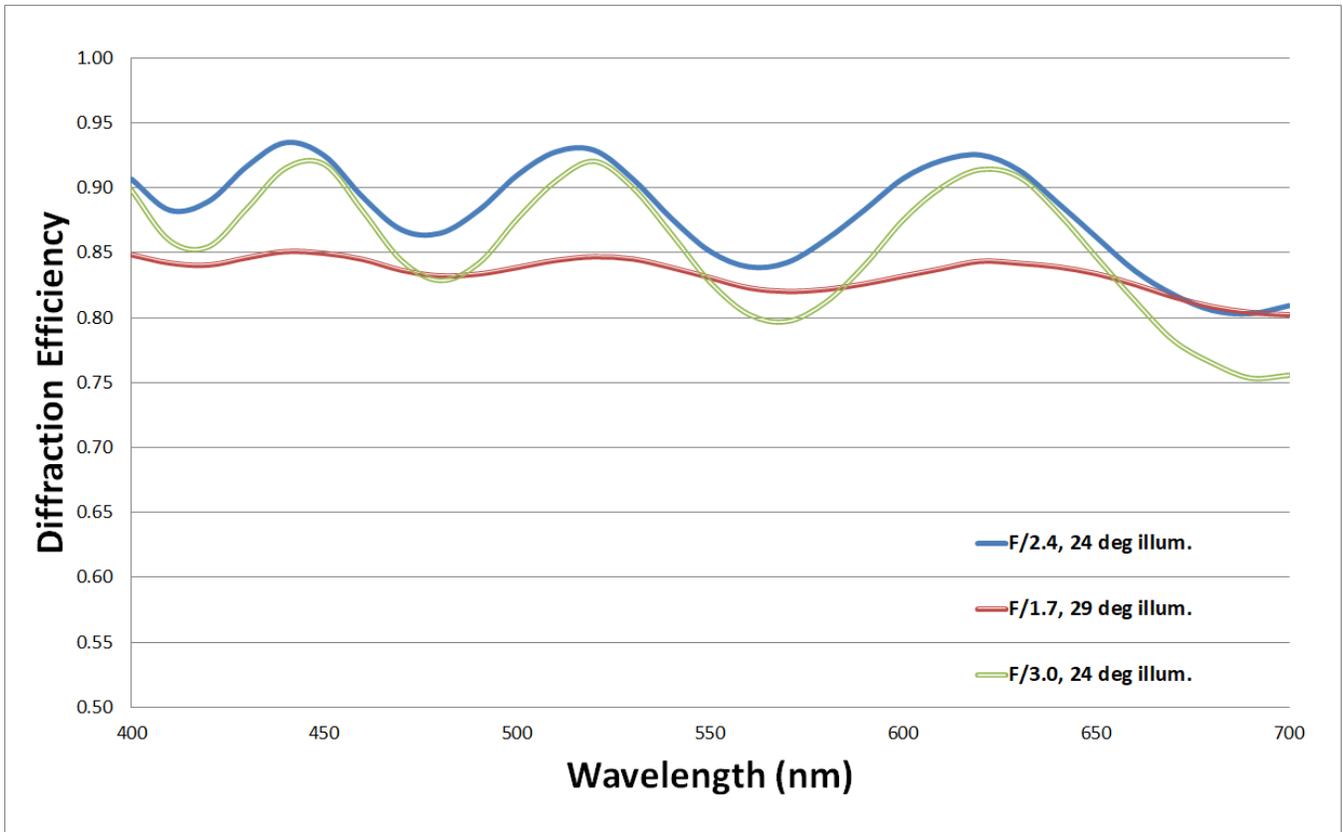


Figure 4-4. 10.8 μ m Pitch DMD Mirror Calculated Diffraction Efficiency

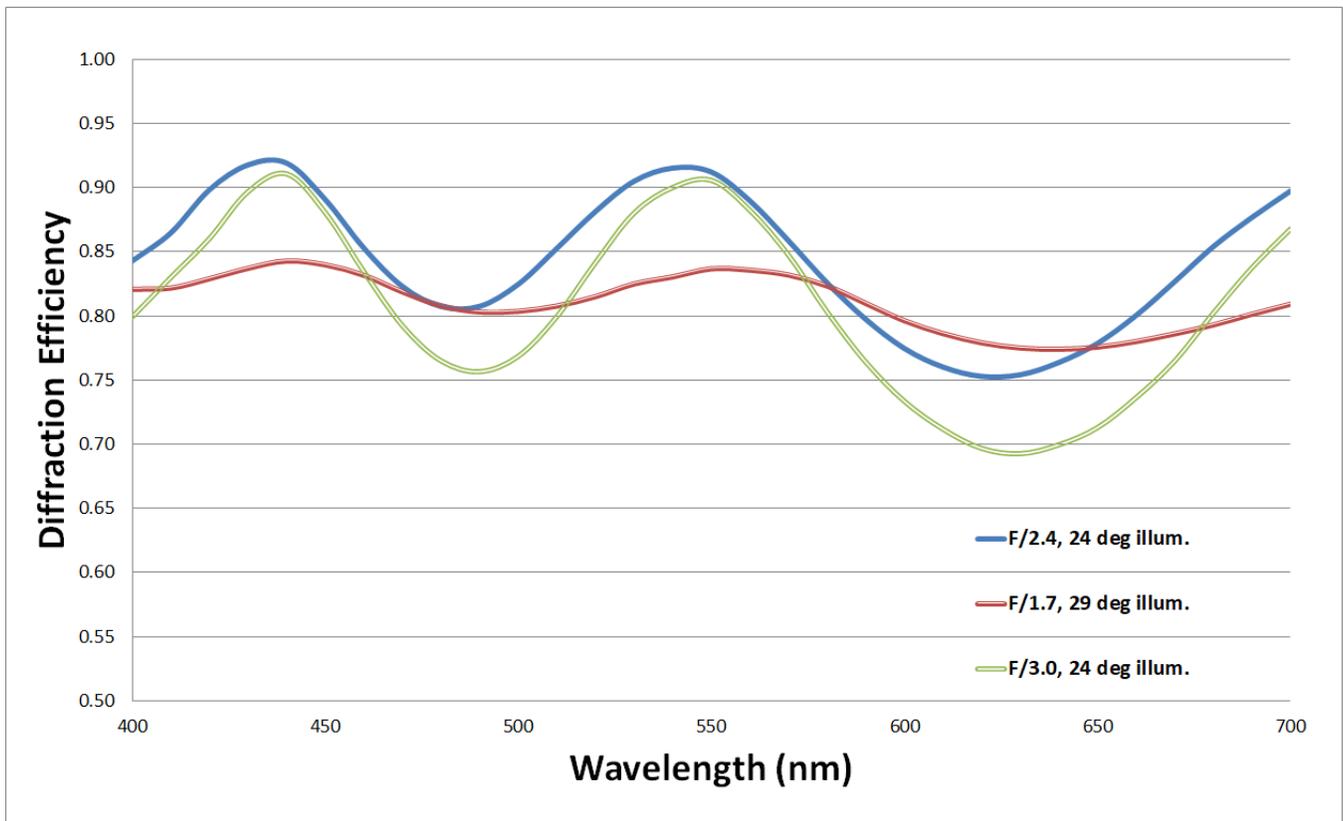


Figure 4-5. 7.6 μm Pitch DMD Mirror Calculated Diffraction Efficiency

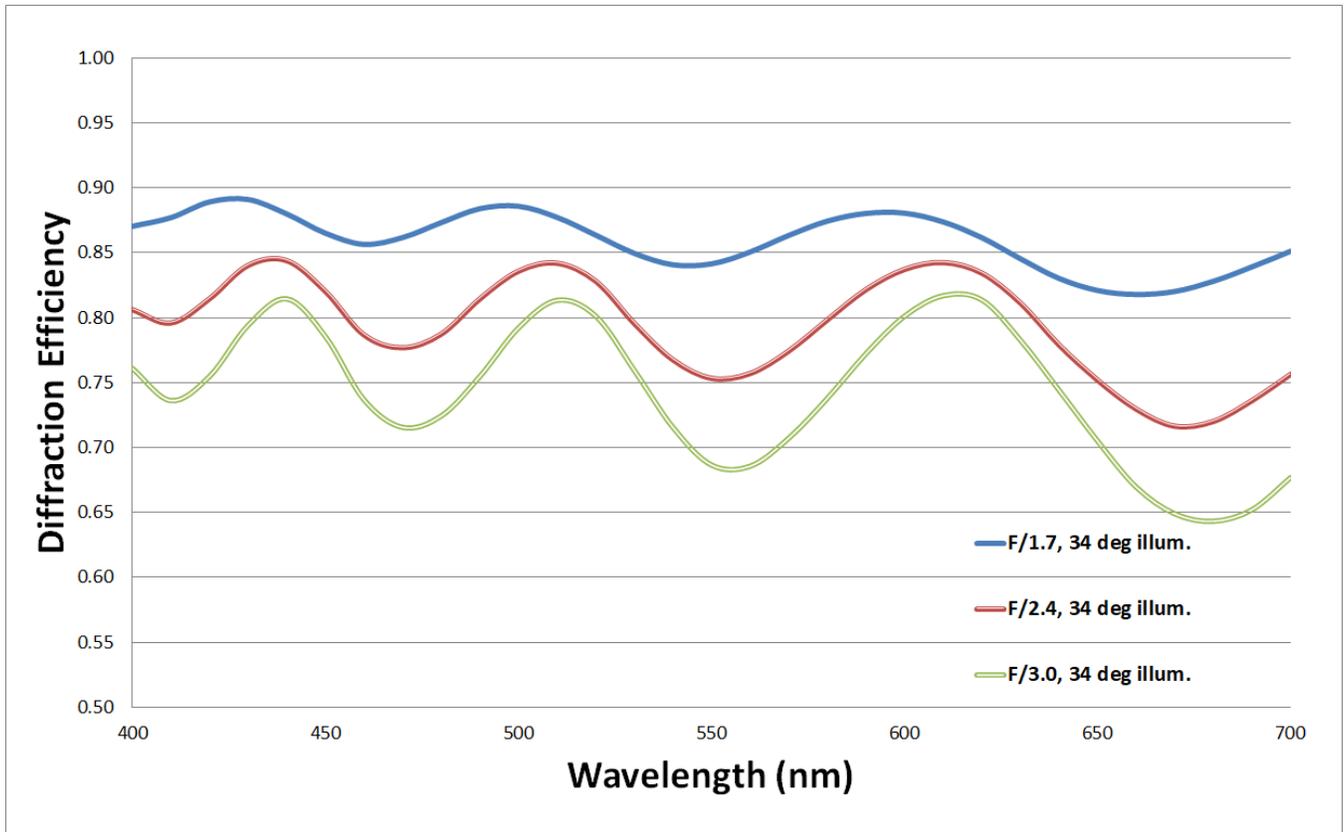


Figure 4-6. 5.4 μm Pitch DMD Mirror Calculated Diffraction Efficiency

Mirror Reflectivity

5.1 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.

Estimating Overall DMD Efficiency

6.1 Estimating Overall DMD Efficiency

Overall optical efficiency can be estimated using [Equation 3](#).

$$Efficiency_{DMD} = transmission_{window} \times efficiency_{fillfactor} \times efficiency_{diffraction} \times reflectivity_{mirror} \times transmission_{window}$$

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 (3)

The photopic numbers shown in this table 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 Efficiency Calculation⁽¹⁾

DMD PITCH	TILT ANGLE (deg)	f/number	DIFF. EFF.	ON-STATE FILL	WINDOW TRANSMISSION (DOUBLE PASS)	MIRROR REFL.	TOTAL EFF.
13.6	12	2.4	89%	92%	96%	89%	70%
10.8	12	2.4	87%	92%	96%	89%	68%
7.6	12	1.7 ⁽²⁾	82%	94%	96%	89%	66%
7.6	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. Refer to DMD data sheet for device-specific values.

⁽²⁾ Illumination angle of 29 degrees used for this case. While this decreases total DMD efficiency, it increases the etendue of the DMD and therefore allows higher maximum brightness. It is likely that image contrast is reduced when compared to nominal illumination angle and f-number case.

Terms and Abbreviations

7.1 Terms and Abbreviations

ABBREVIATION	DESCRIPTION
DMD	Digital Micromirror Device
AOI	Angle of Incidence
WLP	Wafer Level Package

References

8.1 References

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