Application Report

DLPA060A–July 2015–Revised January 2020

System Design Considerations Using TI DLP® Technology in UVA

ABSTRACT

Advanced technologies such as direct imaging lithography and 3D printing often use photoreactive materials optimized for the ultraviolet region of the electromagnetic spectrum. This application report examines some of the thermal, duty cycle, general optical, coherency, and high demagnification design considerations for using a TI DLP® UV digital micromirror device (DMD) that is designed to operate in the UVA region of the UV spectrum.

Trademarks

DLP is a registered trademark of Texas Instruments.

1 Introduction

The UVA region of the ultraviolet spectrum covers wavelengths from 315 to 400 nm. UV DMDs are specifically designed to operate within the upper part of the UVA region. (See each specific DMD data sheet for its specific operational wavelength limits.) The relationship between wavelength and photon energy is given by Equation 1.

$$E = (hc/\lambda) \quad (1)$$

where:

- h is Planck's constant
- c is the speed of light
- λ is the wavelength of the light

Since both values in the numerator of Equation 1 are constants, it shows that photon energy is solely dependent on the reciprocal of wavelength. The smaller the wavelength, the higher the energy carried by each photon. Therefore, light in the UVA range, whose wavelengths are shorter than in the visible region, carries more energy in each photon than light in the visible spectrum.

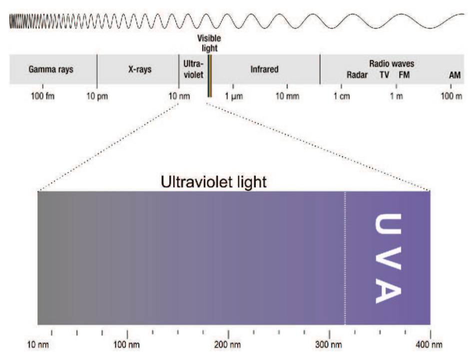

Figure 1. UVA region of the Ultraviolet spectrum

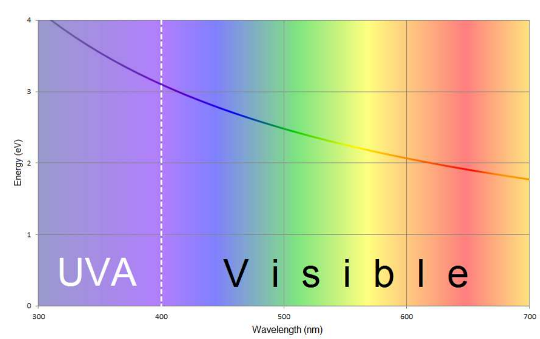

Figure 2. Photon Energy in UVA and Visible Spectrum

In addition to more energy available in each photon, for photosensitive materials, shorter wavelengths of light also allow smaller features to be imaged since diffraction-limited spot size is directly proportional to the wavelength and *f*-number. Examples of applications that benefit from smaller spot size and higher energy per photon are direct imaging lithography and various types of 3D printing. The former typically uses a photosensitive emulsion called a *photoresist*, and the latter uses *photopolymer resins*. These photoresist and resin materials are more reactive to the higher photon energy in the UVA spectrum which results in faster cure rates, and the smaller spot size results in sharper details.

Innovative design techniques, as well as UV-optimized window anti-reflective (AR) coatings, are employed in UV DMDs that are specified to operate in the UVA Spectrum, such as the DLP7000UV, DLP9500UV, and DLP9000XUV DMDs. These DMDs, along with the combination of common photoresists and resins optimized for wavelengths in this band, as well as readily-available Light Emitting Diodes (LED) and laser diodes in this spectral range, create the perfect combination of components to manufacture systems optimized for UVA.

A TI DLP DMD modulates light using reflective micromirrors that switch between two physical states. Since the primary modulation control of a DMD is reflection from inorganic aluminum micromirrors, these devices are significantly more tolerant of shorter wavelengths than spatial light modulator (SLM) technologies that use organic molecules for modulation control. Organic molecules tend to degrade when exposed to these shorter wavelengths of light. [Ref 1,2]

This application note explores the design considerations to maximize the performance of systems that use DMDs in the shorter wavelengths of UVA.

2 Thermal

Although DMD devices are capable of operating at these shorter wavelengths, they are not completely impervious to their higher energy content. DMD array temperature becomes an increasingly important factor when operating in the UVA portion of the spectrum since higher temperatures increase the sensitivity to the higher energy photons.

UVA DMD data sheets requires keeping DMD array temperatures at or below 30°C, with 20°C to 25°C being ideal. This can be accomplished by using an active cooling method such as a liquid cooling system or a thermoelectric cooler (TEC). However, care should be taken to avoid introducing temperature gradients greater than 5°C between any two points on the package or between any point on the package and the DMD array.

Maintaining the temperature and thermal gradient within the specifications defined in the data sheet helps promote optimal performance of the DMD when used with higher energy photons.

3 Duty Cycle

Within all applications, the DMD benefits from operating at an average 50% landed-on/off duty cycle, but this consideration becomes even more relevant when operating under UVA wavelengths. The landed-on/landed-off duty cycle indicates the percentage of time that an individual micromirror is landed in the on-state versus the off-state. The switching time taken to switch between states is considered negligible and is ignored when determining this duty cycle.

This duty cycle is expressed as the landed-on percentage divided by the landed-off percentage. For example, a pixel that is landed-on 75% of the time and landed-off 25% of the time is denoted as 75/25 duty cycle. Note that the two numbers that express duty cycle will always sum to 100.

Operating at or near 50/50 duty cycle promotes the longest DMD performance. There are two possible scenarios of operation under this consideration:

1. The first scenario is when the duty cycle histories of the DMD pixels are not tracked and subsequently are not known. In this situation, operating the DMD at 50/50 whenever the DMD is not actively illuminated[(1)] drives all pixel duty cycle historical averages back toward 50/50 duty cycle. The longer the DMD is operated at 50/50 in any and all available system quiescent periods, the closer the overall historical average approaches 50/50 duty cycle.

CAUTION

[1] DMD illumination subsystems (Lamps, LED, Lasers) must be disabled or shuttered at any time that DMD patterns are not needed or are not being projected to the fabrication surface. Do not use the DMD as the primary illumination shutter.

2. The second scenario is when the history of each individual pixel is tracked over time. In this case, applying the reverse duty cycle to each pixel for an equal period of time (when not actively being used for patterning) will cause the historical average for each pixel to approach 50/50 accumulated duty cycle. For example, if a pixel is driven at 62/38 duty cycle during operation, then driving the pixel at 38/62 duty cycle for an equivalent time during quiescent periods will cause the pixel average duty cycle to approach 50/50. Note that it is also possible to drive at a higher reverse duty cycle for a shorter period of time so that the overall average is 50/50.

4 Optical

In systems with one-to-one or greater magnification, designing illumination and output optics with ƒ-numbers [1] ƒ-numbers as small as ƒ/2.4 are practical and desirable. Matching the illumination and projection ƒ-numbers too closely can result in a significant loss of power at the focal plane (fabrication surface). Slightly under-filling the output pupil provides DMD tilt variation tolerance in an optical system. For example, illuminating with ƒ/3 into an ƒ/2.4 output allows the image of the illumination pupil to remain within the output aperture. This is discussed in more detail in *Section 5.1*.

It is further recommended that an illumination adjustment mechanism allowing adjustment of ±2° from the nominal incident angle be employed in a system design. Typically the illumination cone is centered on an angle that is 24° from the window normal so that the output cone is centered on the DMD normal for 12° tilt angle devices. The ±2° adjustment will allow the brightest order(s) to be moved into the output aperture.

These and other DLP optical system considerations are discussed in greater detail in *DLP System Optics* (DLPA022). The following sections examine considerations for high demagnification systems.

[1] The definition of ƒ-number as used here is the effective focal length of the lens ƒ divided by the diameter of the aperture of the lens.

5 High Demagnification Systems

Projection systems using DLP technology typically use an illumination design as shown in Figure 3. Note that the *flat* state is not an operational DMD micromirror state, but must be accounted for when designing an optical system.

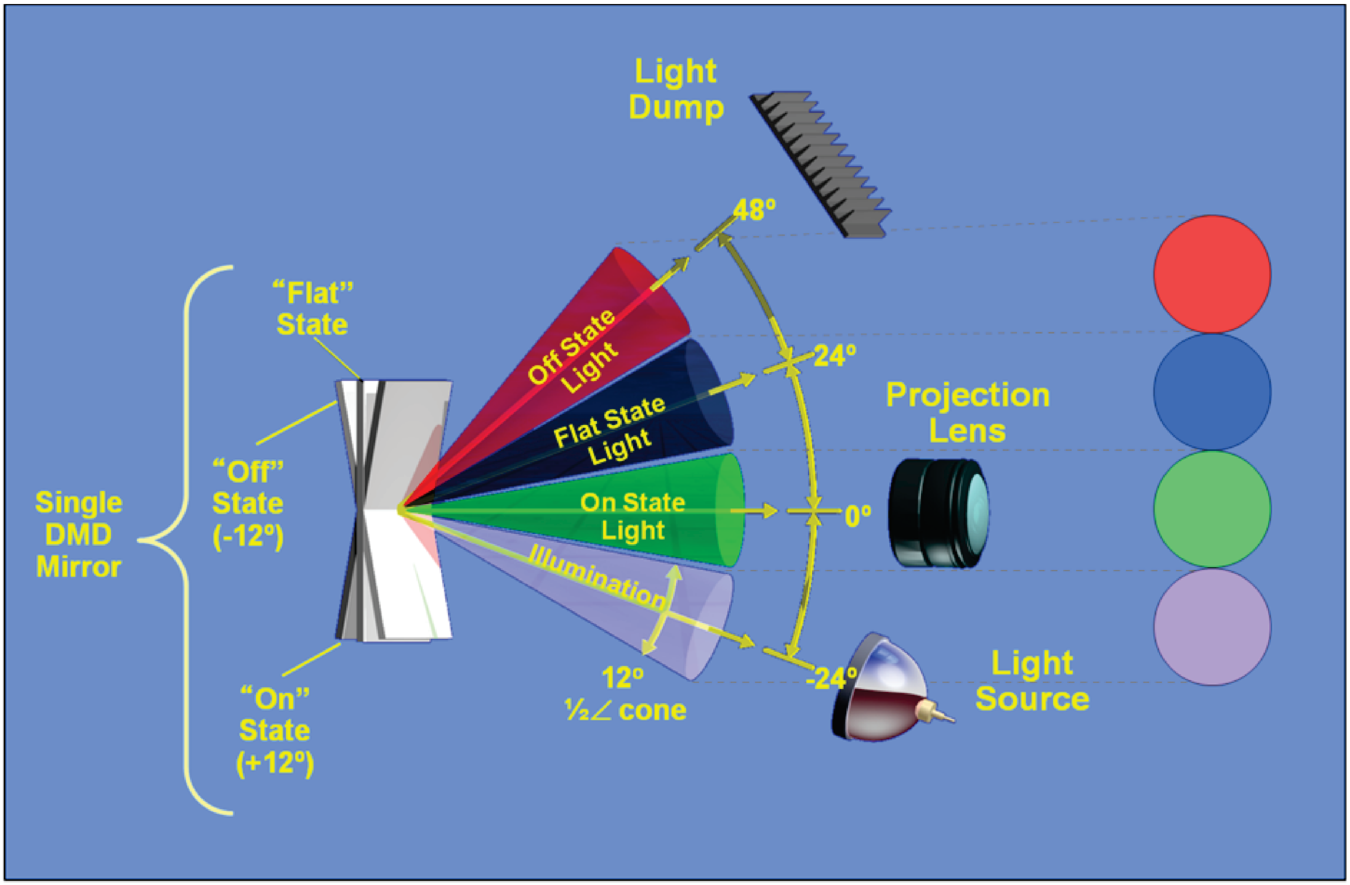

Figure 3. Typical Projection System Optics

However, some lithography and 3D print systems may use demagnification of the DMD array image to address very small features down to 1 µm or smaller. Figure 4 demonstrates the small size for the output aperture of a high demagnification system vs the size of a typical projection optical system.

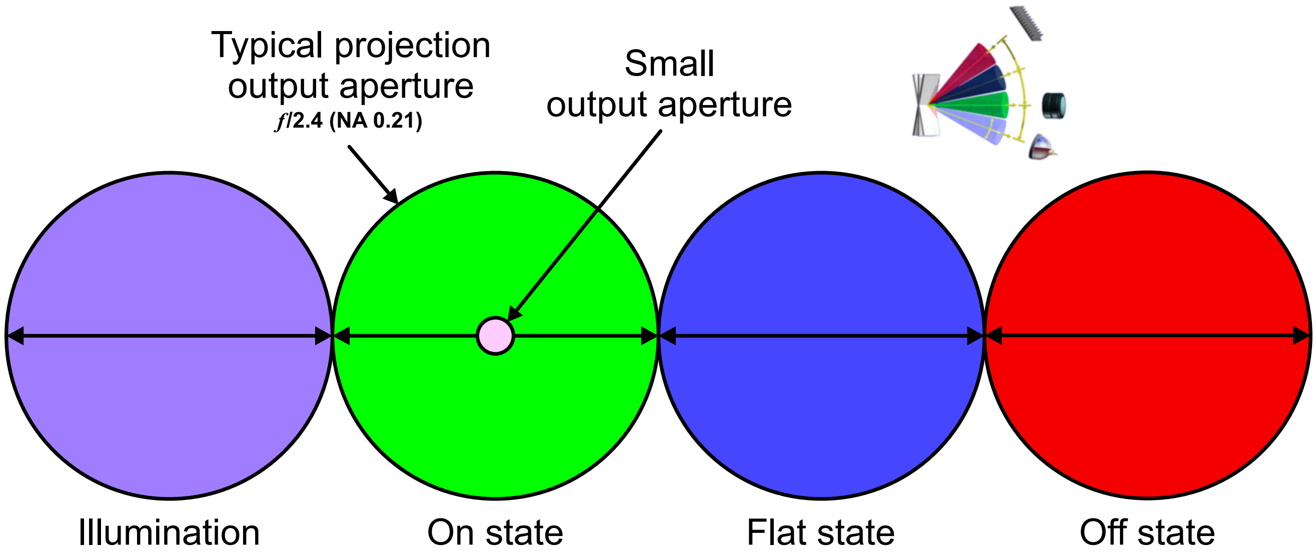

Figure 4. Light Distribution at Projection Lens Entrance Pupil (Typical Projection System vs High Demagnification)

Considerations for these relatively small apertures typical of high demagnification are divided into two areas: incoherent sources and coherent sources.

5.1 *Incoherent Sources (Lamps and LEDs)*

For broadband and LED sources(2) that precisely match the size of the DMD reflected output bundle to the input illumination bundle, DMD micromirror tilt variations may shift the reflected bundle such that reflected light spills to the side and is obscured by the output aperture as shown in the panels of Figure 5. This results in undesired loss of total output brightness with an added potential for image brightness non-uniformity.

CAUTION

(2) When a DMD is used with incoherent sources, a filter which nearly extinguishes all wavelengths below the DMD minimum specified wavelength must be used in the illumination path to the DMD (see the individual data sheet specification). Some LEDs may not have significant spectral content below the DMD minimum specified wavelength thereby obviating the need for a filter.

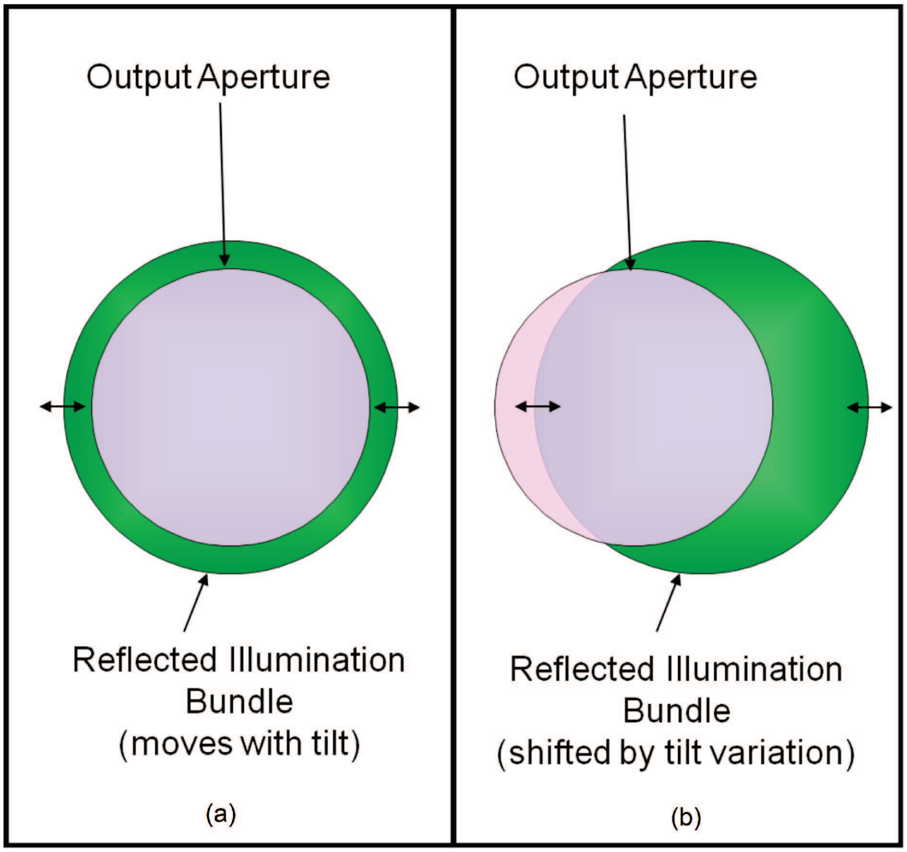

Figure 5. Small Output Aperture

The best way to capture all of the light with tolerance for micromirror tilt variation is to make the illumination bundle smaller than the output aperture. This allows all of the light to be captured, as illustrated in Figure 6:

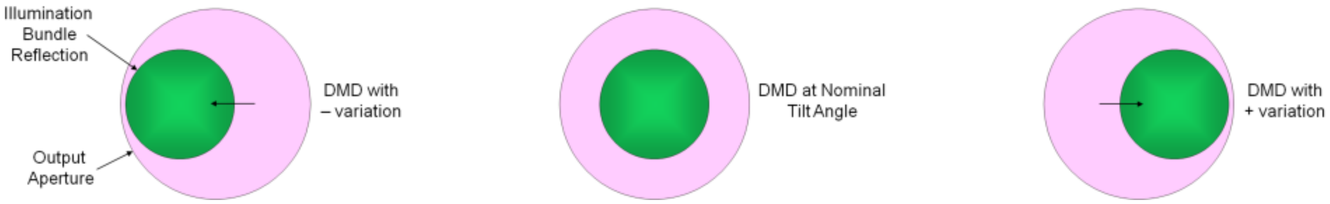

Figure 6. Reflected Illumination Movement with Tilt Variation

For the current UVA capable DMDs, the tilt variation specification is ±1°. At the output aperture the reflected illumination moves 2x this amount, ±2°, since the reflected rays move 2x the movement of the reflecting surface. The output aperture is recommended to be 4° larger in diameter than the illumination bundle to encompass this range (–2° to +2°). This example assumes a nominal 12° illumination and does not include adjusting the illumination angle as recommended in the previous Section 4 section.

Therefore an effective limit exists on the largest f-number (smallest aperture) at the output that can be achieved to provide the 4° of tolerance. Even for a perfectly collimated illumination beam with an angular extent of zero degrees, the aperture would have an f/14.3 equivalent, which is a cone with an angular diameter of 4°.

This results in a practical limit on the demagnification that can be reached with this tolerance. Optics with an *ƒ*-number of less than one are very difficult to build. If a limit of *ƒ*/1 is used, then a demagnification of 13x is the largest possible demagnification. The graph in Figure 7 shows two curves. The magenta curve is the angular diameter of the cone at the DMD output aperture that results in an *ƒ*/1 cone at the fabrication surface. The green curve is the allowable angular diameter of the illumination bundle that maintains a 4° margin between the illumination bundle and the output aperture. Note that the allowable illumination cone diameter reaches zero just past 13x demagnification.

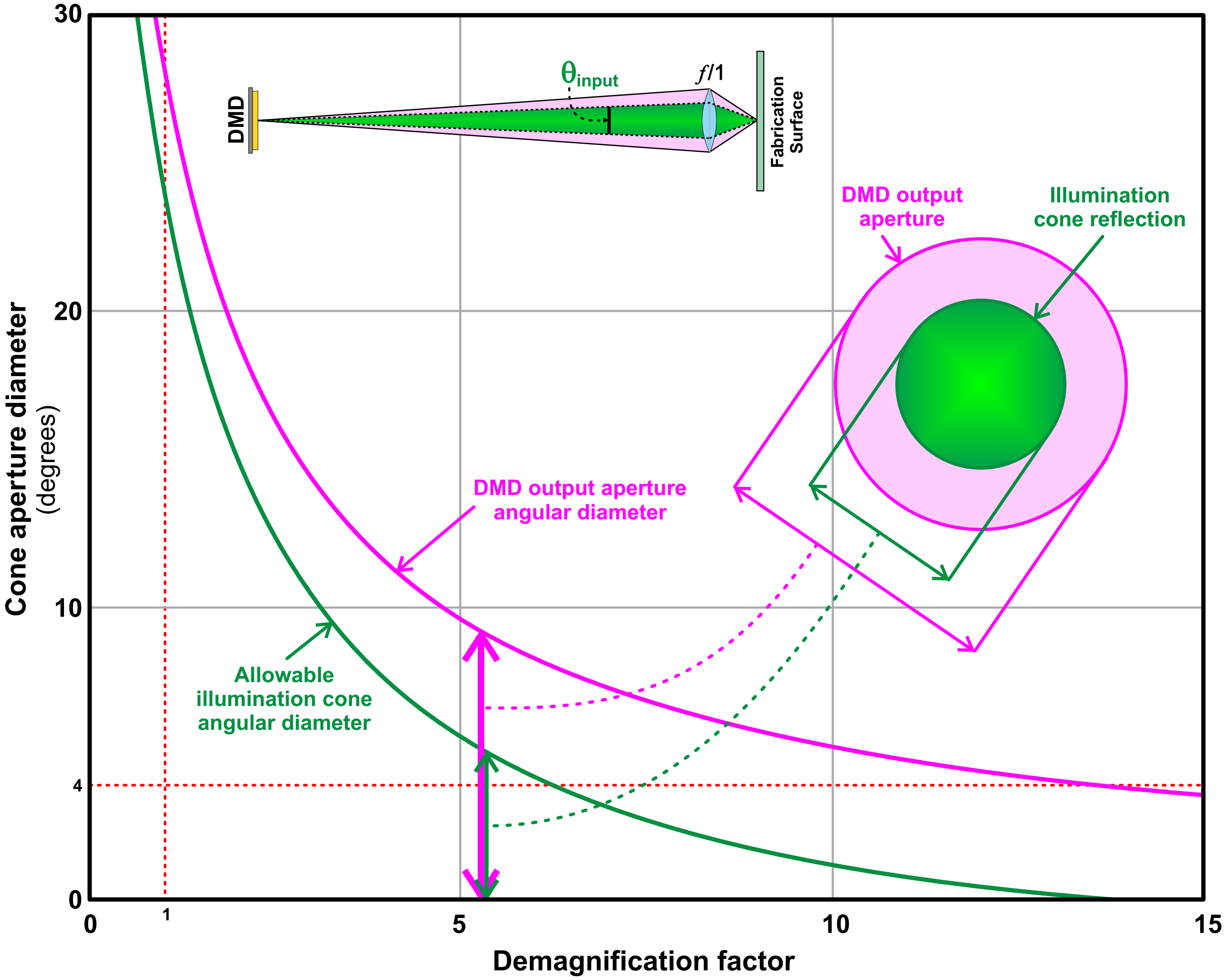

Figure 7. DMD Output Aperture Diameter vs Demagnification

Equation 2 approximates the maximum achievable demagnification for a given f-number.

$$\frac{\cot\left(\frac{\theta_{input} + 4^\circ}{2}\right)}{2(f/\#)} - 1 \quad (2)$$

where:

- θ_{input} is the angular extent of the input illumination bundle.

In summary, incoherent sources have two limits when used in high demagnification systems. The output is recommended to have an f-number of less than f/14.3 and a demagnification of 13x or less. In practice, the angular diameter of the illumination bundle is several degrees so that either some aperture margin is sacrificed or a lower demagnification chosen. If the optical design includes options for independently aligning the DMD with the output optics and illumination source angle, higher f/# and demagnification values are possible.

5.2 Coherent Sources (Lasers)

When a DMD is illuminated with coherent, collimated, narrow-band light, the reflected result is a two-dimensional pattern of spots called *diffraction orders*. A continuum of conditions from a full *blaze* to a complete *anti-blaze* condition may exist depending on the pixel pitch, DMD micromirror tilt angle, illumination wavelength, and the incident angle of the illumination light.

A blaze condition exists when one diffraction order contains the majority of the energy in the overall diffraction pattern. Modeling indicates that this single order can contain nearly three-quarters of the output energy, with the remaining quarter being distributed into all of the other orders. This is the best possible case. Optical systems designed to operate at a blaze condition can use much smaller angular apertures, but will likely require DMD alignment capabilities with both illumination and projection optical path angle adjustments to correct for differences in nominal tilt angle variations from one DMD to another.

An anti-blaze condition exists when the four brightest orders contain equal amount of energy in the diffraction pattern. Modeling indicates that these four adjacent orders can each contain roughly one sixth of the total output energy (approximately two-thirds in total), with the remaining third being distributed in each of the remaining orders.

Basic DMD diffraction is discussed in more detail in *Using Lasers with DLP DMD Technology* (DLPA037).

For the UVA capable DMDs, the maximum specified tilt variation between individual micromirrors is ±1°. In the UVA region, this tilt angle difference is such that customers may receive a DMD that results in a condition that ranges from anti-blaze condition to blaze condition. Therefore, the system output optics should have sufficient aperture to collect, at the very least, the four brightest orders in an anti-blaze condition. For example, at 363 nm, a 10.8-µm pitch device requires an angular aperture at least 2.7° in diameter. By increasing the diameter to 3.9°, four to five orders are captured, which is recommended. This recommended diameter is calculated by $\sin^{-1}(2\lambda/d)$, where λ is the wavelength and d is the pixel pitch.

Coherent light sources require additional design considerations. The reflected output will result in a set of *diffraction orders* rather than a single reflected bundle of light. These orders each have the same angular extent as the input bundle. Consequently, a collimated beam, which has virtually no angular extent, results in collimated diffraction orders.

The output aperture will *see* some number of these diffraction orders. If the angular diameter is smaller than $\sin^{-1}(\lambda/d)$ (where d is the pixel pitch of the DMD), then it is only possible to capture one order in the output aperture, as illustrated in the panels of Figure 8.

If the incident illumination angle is fixed, variations in tilt angle do not cause the diffraction orders to move, but do cause the energy distribution to shift between the orders. Consequently, if the order captured is near a blaze condition, most of the energy available will be captured in this one order (panel (a) in Figure 8), but if the condition is near an anti-blaze point, this small aperture will only capture a fraction of the output (panel (b) in Figure 8).

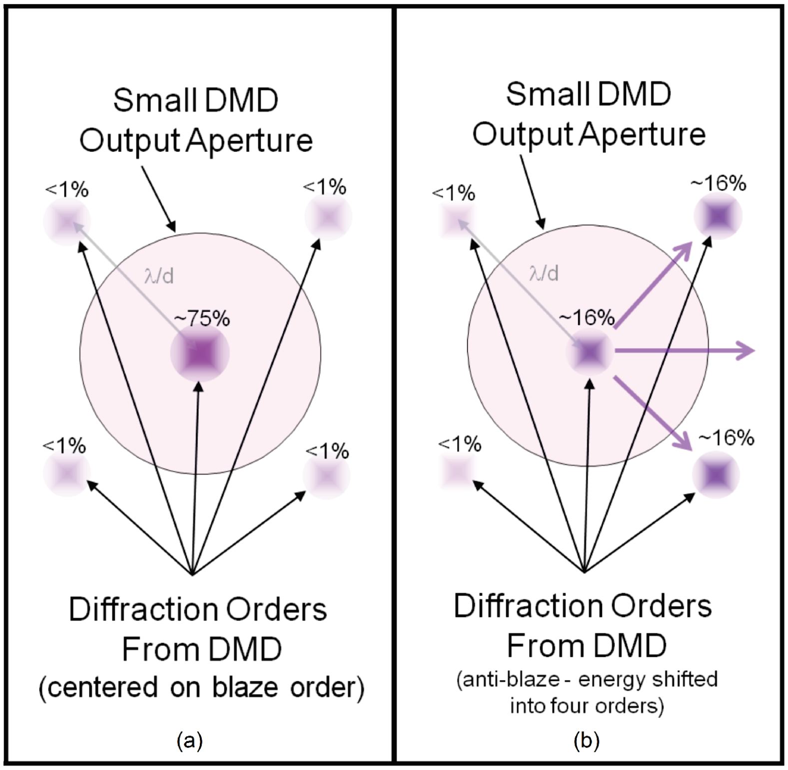

Figure 8. Diffraction Orders with Coherent Illumination

To provide tolerance in the system design it is recommended that the output aperture be expanded to capture four to five orders as shown in Figure 9. As shown in the previous example, with a 10.8-µm pixel pitch DMD with collimated light at 363 nm, the minimum angular diameter of about 2.7° captures one or four orders, and 3.9° captures four or five orders. Equation 3 gives the recommended minimum angular diameter:

$$\sin^{-1}(2\lambda/d) + \theta_{input} \quad (3)$$

where:

- θ_{input} is the angular extent of the input illumination bundle.

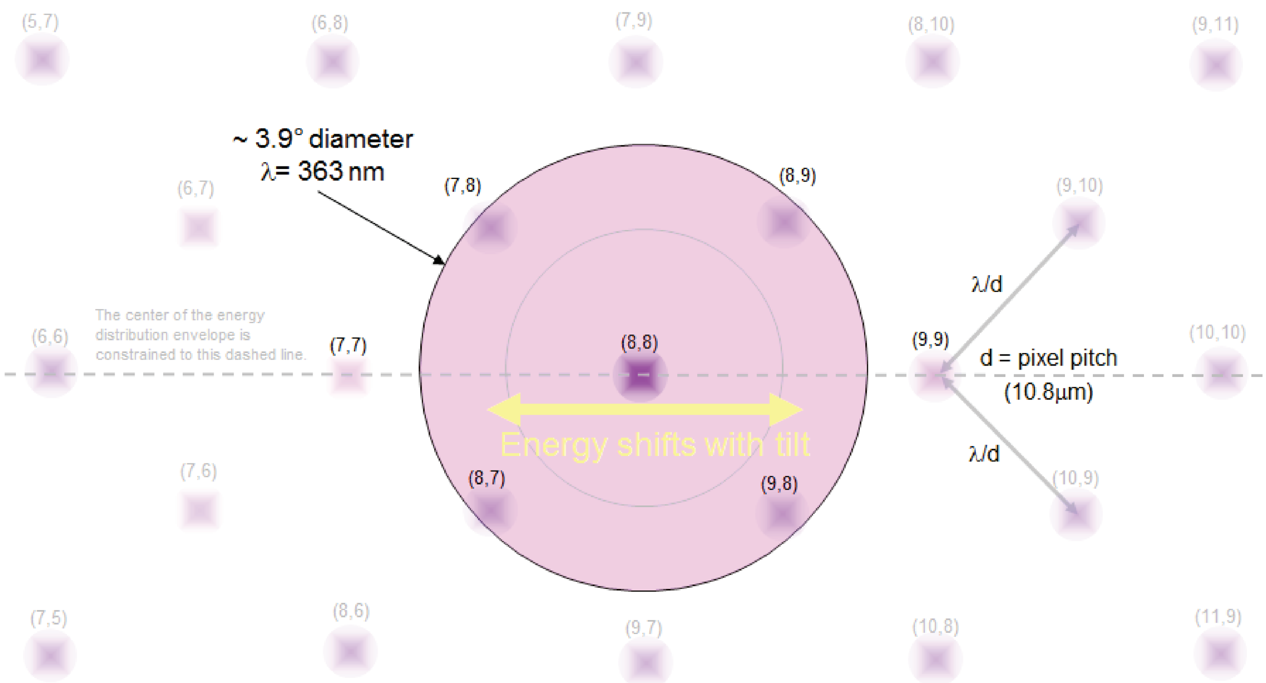

Figure 9. Expanded Output Aperture Capturing Five Orders

Although the orders do not move with variations in tilt angle, they do move with changes in the illumination angle. If the illumination is moved by an angle of θ, the orders at the output will move by approximately –θ. Therefore, it is recommended to include a mechanism to adjust the input illumination angle by ±2° which allows the four to five orders with the highest intensity to be captured in the output aperture.

Once the illumination angle and the projection angles are established, the projected DMD orders should not move due to differences in DMD tilt angle. However, the power in each order may vary due to DMD tilt angle. Figure 10, Figure 11, and Figure 12 show the power and the positions of the major orders as they are affected by tilt angles of 11, 12, and 13 degrees of a 7.56 µm pitch DMD for the specific wavelength of 365 nm. The center of the projection aperture is shown as a + symbol and the center of the projection is defined by the purple diamond shape. The orders are purple circles where the area of each circle symbolizes the relative amount of power in that specific order. Once the illumination and projection angles are established and fixed in place, notice with tilt angle change (11-12-13°) how the orders do not shift within the projection aperture but how the power moves from certain orders to other orders. This indicates the importance of having the appropriate projection aperture size that allows maximization of output power collection while taking into account DMD tilt angle as well as illumination and projection alignments.

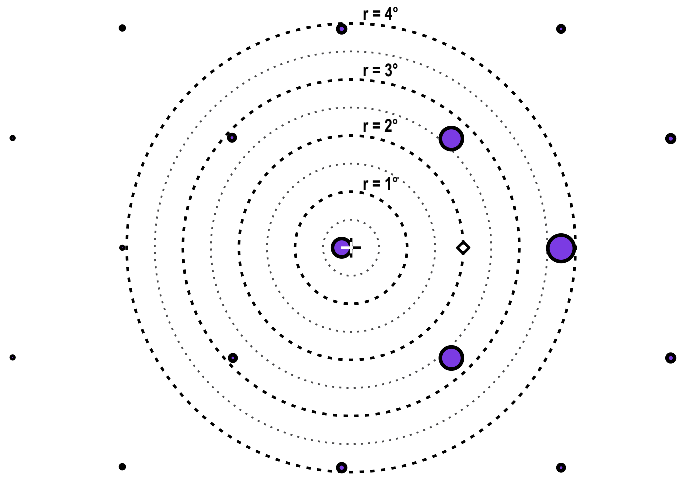

Figure 10. Order power diagram, 11° tilt angle, λ = 365 nm, 7.56 µm pixel pitch

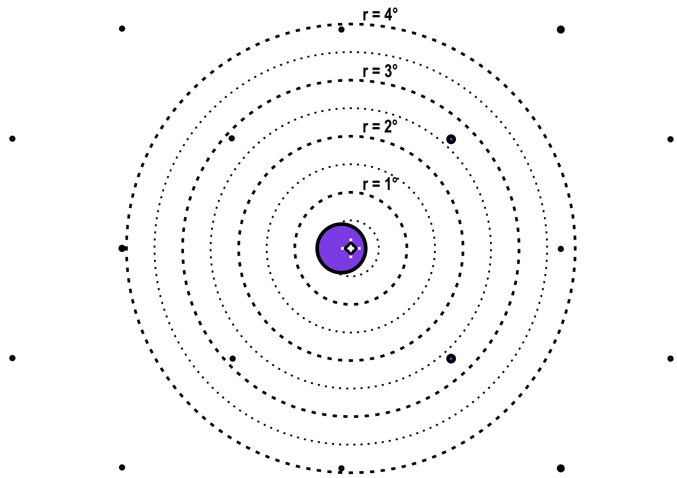

Figure 11. Order power diagram, 12° tilt angle, λ = 365 nm, 7.56 µm pixel pitch

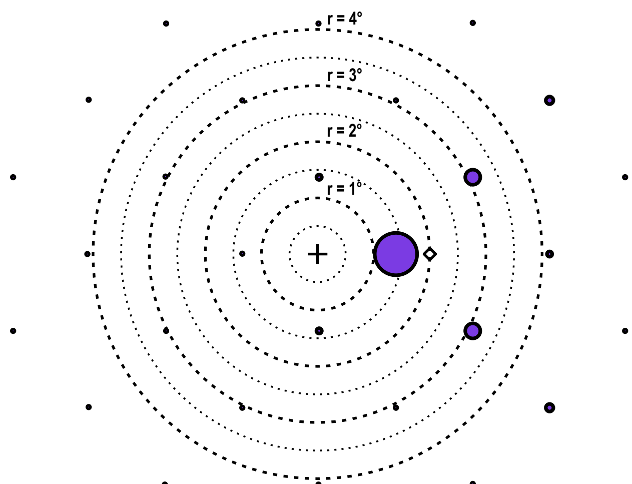

Figure 12. Order power diagram, 13° tilt angle, λ = 365 nm, 7.56 µm pixel pitch

Figure 13, Figure 14, and Figure 15 show the power and the positions of the major orders as they are affected by tilt angles of 11, 12, and 13 degrees for **10.8 um pixel DMDs**.

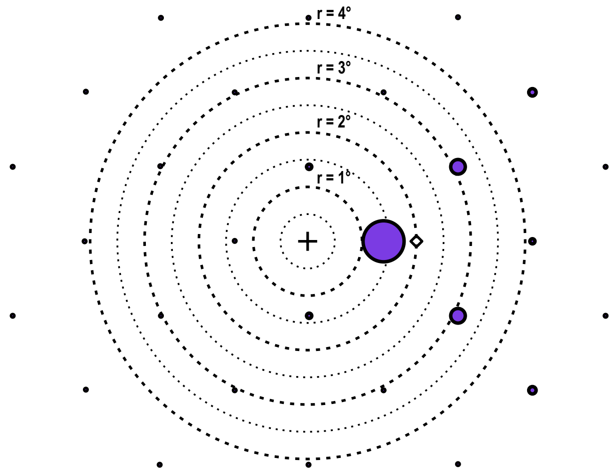

Figure 13. Order power diagram, 11° tilt angle, λ = 365 nm, 10.8 µm pixel pitch

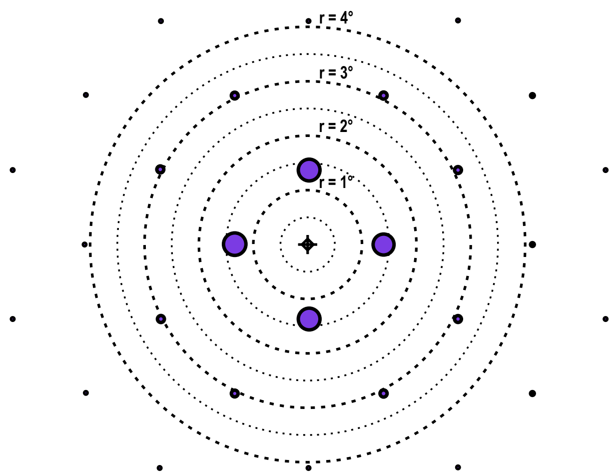

Figure 14. Order power diagram, 12° tilt angle, λ = 365 nm, 10.8 µm pixel pitch

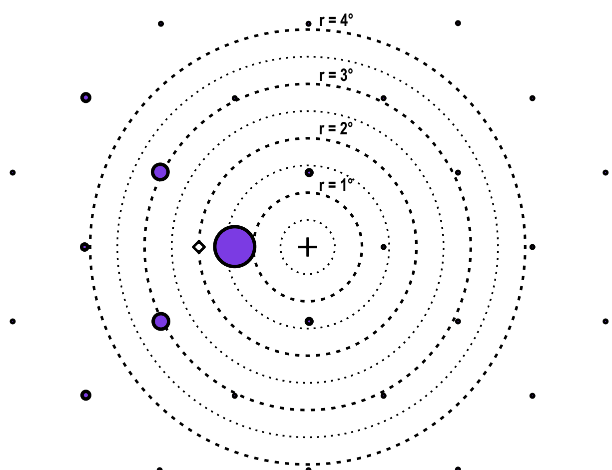

Figure 15. Order power diagram, 13° tilt angle, λ = 365 nm, 10.8 µm pixel pitch

As with the incoherent case, the angular diameter of the output aperture sets a practical limit on the demagnification level that can be achieved. For example, at 363 nm the maximum demagnification for a 10.8 µm pixel pitch DMD using collimated light is a factor of approximately 13.9x. If the incident beam has angular extent, its diameter should be added to the output aperture before determining the demagnification achievable.

In general, the maximum demagnification achievable can be determined by the f-number of the focusing optics relative to the fabrication surface, and then setting the distance to the DMD so that the aperture diameter is the minimum recommended (see Equation 3). Equation 4 gives an estimate of the maximum attainable demagnification.

$$\frac{\cot\left(\sin^{-1}\left(\frac{\lambda}{d}\right)+\frac{\theta_{input}}{2}\right)}{2(f/\#)}-1 \quad (4)$$

where:

- θ_{input} is the angular extent of the input illumination bundle.

In summary, coherent sources have the same two limits as incoherent sources. However, the minimum aperture is determined by the angular spacing of diffraction orders rather than the tilt tolerance alone, which in turn limits the maximum practical demagnification.

6 Conclusion

Adhering to the recommendations outlined here will maximize the performance of a DLP technology UV-enhanced DMD when integrating into applications using light sources in the UVA spectrum.

To learn more, see the following links:

- *Getting Started with DLP Technology*
- *Using Lasers with DLP DMD Technology* (DLPA037)
- *DLP System Optics* (DLPA022)
- *DLP Applications*
- *DLP Application Notes and White Papers*

7 References

1. Lin, Pao-Tai, Shin-Tson Wu, Chin-Yen Chang, and Chain-Shu Hsu.Mol. Cryst. Liq. Cryst., Vol. 411, pp. 243=[1285]–253=[1295], 2004, *UV Stability of High Birefringence Liquid Crystals*
2. Wen, Chien-Hui, Sebastian Gauza, and Shin-Tson Wu.LIQUID CRYSTALS, VOL. 31, NO. 11, NOVEMBER 2004, 1479–1485, *Ultraviolet stability of liquid crystals containing cyano and isothiocyanato terminal groups*

Revision History

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

Changes from Original (July 2015) to A Revision **Page**