Application Report
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# System Design Considerations Using TI DLP® Technology down to 400 nm

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## ABSTRACT

Direct imaging lithography, 3D printing and other systems often use photo-reactive materials optimized for the deep blue region of the visible spectrum. This application report examines some of the thermal, duty cycle, general optical, coherency, and high de-magnification design consideration for using TI DLP® Digital Micromirror Devices [DMD] that are specified to operate down to 400 nm.

Topic Page

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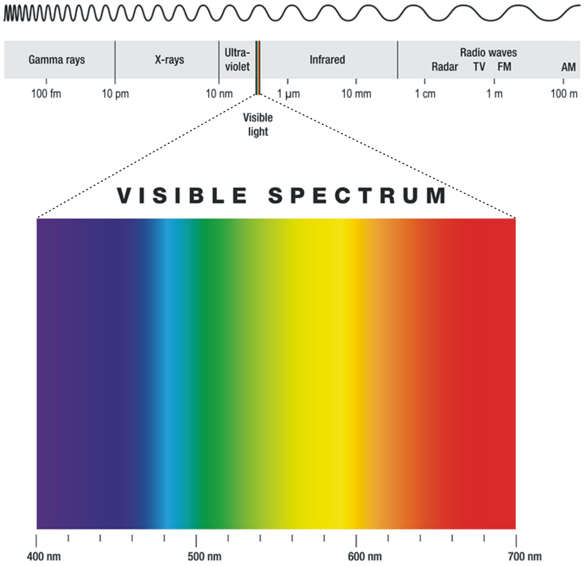
## 1 Introduction

The line of demarcation between Ultra Violet [UV] and visible wavelengths is generally considered to be 400 nm. The relationship between wavelength and photonic energy is given by $E = (hc/\lambda)$ where $h$ is Plank's constant, $c$ is the speed of light, and $\lambda$ is the wavelength of light.

This equation shows that photonic energy is solely dependent on the reciprocal of wavelength since both numbers in the numerator are constants. The smaller the wavelength the higher the energy carried by each photon. Therefore deep blue light, whose wavelengths are closer to the 400 nm boundary, carries more energy in each photon than light in other regions of the visible spectrum.



Examples of applications that benefit from higher photonic energy are direct imaging lithography and some types of 3D printing. The former typically uses a photosensitive emulsion called a "photoresist" and the latter a photopolymerized resin. These photoresist and resin materials are more reactive to higher photonic energy resulting in faster cure rates.

Innovative design techniques are employed in Digital Micromirror Devices [DMD] specified to operate down to 400 nm. Some examples are the DLP6500FLQ, and DLP9000FLS. In particular 405 nm light can be used with this type of DMD. Light Emitting Diodes [LED] and laser diodes at this wavelength are readily available at reasonable cost, making their use attractive in systems that use 405 nm optimized materials.

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 aluminum micromirrors, these devices are significantly more tolerant of shorter wavelengths than spatial light modulator [SLM] technologies that use organic molecules for modulation control since such molecules tend to degrade when exposed to these shorter wavelengths of light. [Ref 1,2]

The same trait that makes shorter wavelengths suitable for lithography and 3D print systems requires attention to design considerations when used with a DMD. These considerations are explored in this application note.

## 2 Thermal Considerations

Although DMD devices are capable of operating at shorter wavelengths they are not completely impervious to their effects. DMD array temperature becomes an important factor when operating in the deep blue portion of the spectrum.

It is ideal to keep DMD array temperatures below 30° C with 20° to 25° C preferred. This can be accomplished with passive or even active cooling such as a Thermo Electric Cooler [TEC]. However, care should be taken to avoid introducing temperature gradients greater than 10° 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 Considerations

All applications benefit from operating the DMD near 50% landed on/off duty cycle, but this consideration becomes more important in the shorter wavelength arena. The landed-on/landed-off duty cycle indicates the percentage of time that an individual micromirror is landed in the on state vs. the off state. The switching time between states is considered negligible and ignored when determining this duty cycle.

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

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

The first scenario is when the pixel histories are not known or tracked. Operating the DMD at 50/50 whenever the DMD is not actively being illuminated(1) drives the average back toward 50/50. The longer it is operated at 50/50 in quiescent periods the closer the overall average will be to 50/50.

**NOTE:** (1) Illumination should be shuttered or turned off at any time that DMD patterns are not needed or being used at the fabrication surface. Do not use the DMD as the primary illumination shutter.

The second scenario is when the history of each pixel is tracked. In this case the pixels can be operated in the inverse duty cycle for an equal period of time when not actively being used for patterning and at 50/50 after that. For example, if a pixel is driven at 62/38 for four hours during operation, then driving it at 38/62 for four hours during quiescent periods averages to 50/50.

## 4 Coherency Considerations

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 “blaze” or an “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 most of the energy in the overall diffraction pattern. Modeling indicates that this order can contain nearly three-quarters of the output energy, with the remaining quarter being distributed into all of the other orders.

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 a sixth of the output energy (approximately two-thirds in total), with the remaining third being distributed in all of the other orders.

Basic DMD diffraction is discussed in more detail in the white paper Using Lasers with DLP® DMD Technology.

The maximum specified tilt variation between individual micromirrors is ± 1°. Near 400 nm this tilt angle difference is such that customers may receive a DMD that results in any condition from anti-blazed to blazed. 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 405nm, a 7.56 µm pitch device requires an angular aperture at least 4.4° in diameter. By increasing the diameter to 6.2°, four to five orders are captured, which is recommended.

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.

## 5 Optical Considerations

In systems with one-to-one or greater magnification, designing illumination and output optics with *ƒ* numbers as small as *ƒ*/2.4 are practical and desirable, since slightly under-filling the output pupil provides 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.

General DLP optical system considerations are discussed in greater detail in the DLP® System Optics application note. The following sections examine considerations for high de-magnification systems.

## 6 High De-magnification System Considerations

Consumer projection systems using DLP technology typically use an illumination design as shown in Figure 1.

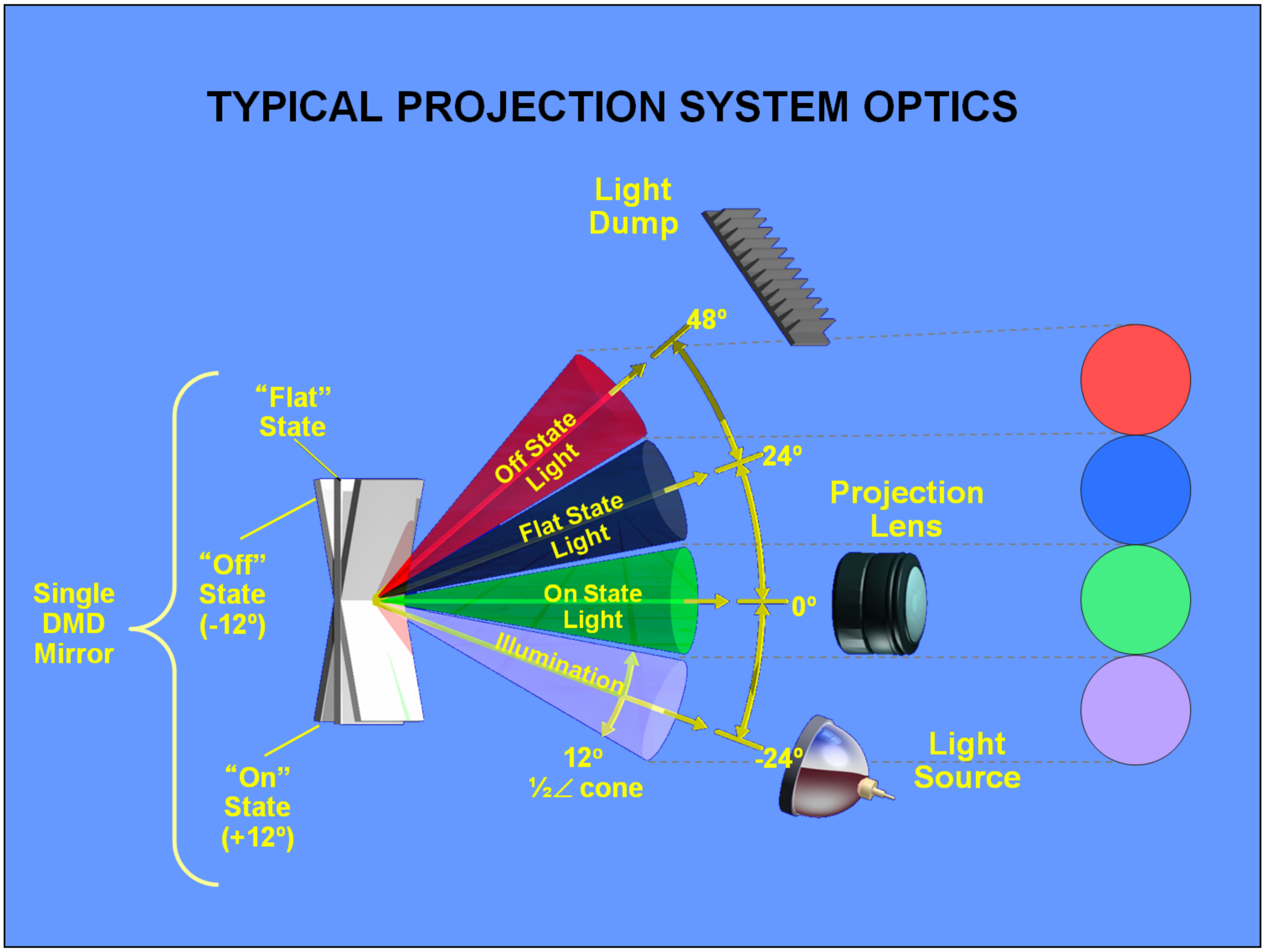


Figure 1. Typical Projection System Optics

However, some lithography and 3D print systems may use de-magnification of the DMD array image to address very small features down to 1 µm. Figure 2 shows the small size of the output aperture of such systems relative to a traditional projection optical system.

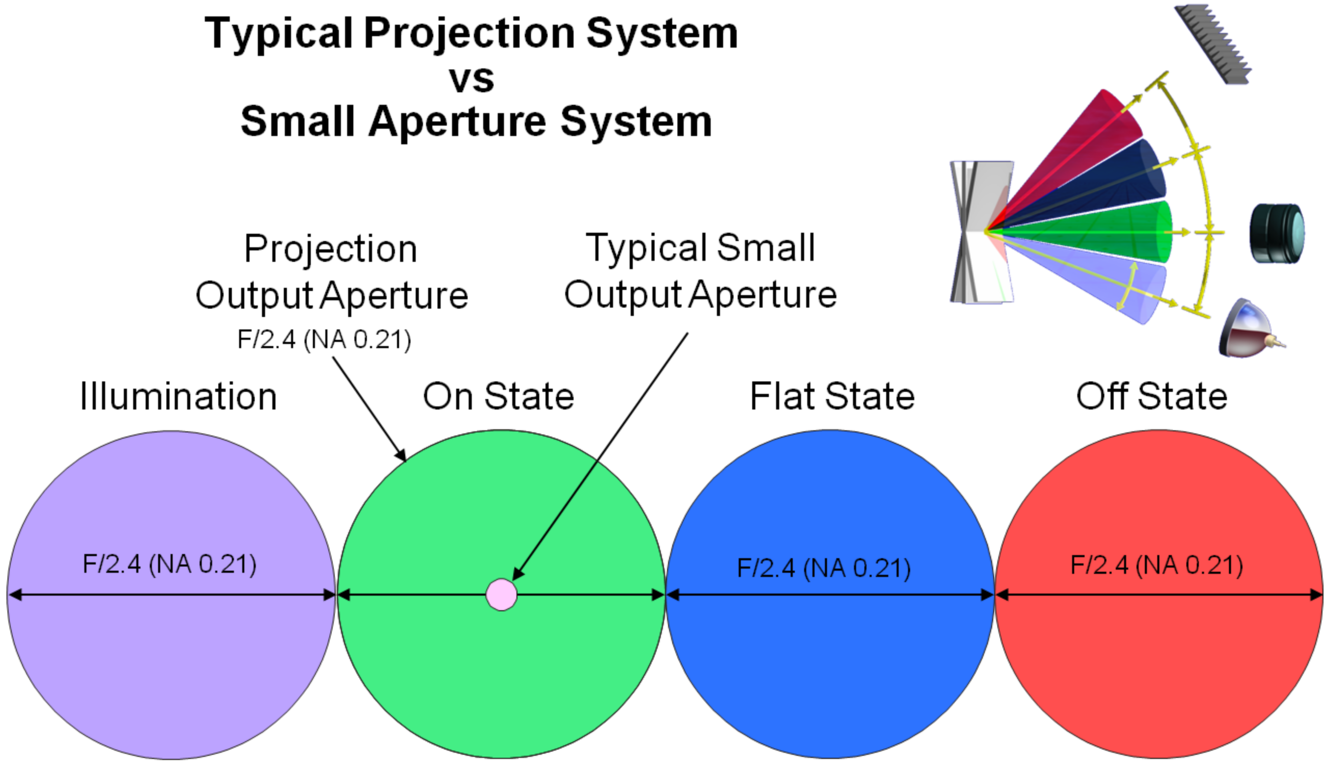


**Figure 2. Light Distribution at Projection Lens Entrance Pupil**

Considerations for these relatively small apertures are divided into two areas – incoherent sources and coherent sources.

### 6.1 *Incoherent Sources (Lamps and LEDs)*

For broadband and LED sources(2) that match the size of the illumination bundle to the DMD output bundle, the micromirror tilt variations may allow some light to spill off of the side or not completely fill the output aperture as shown in Figure 3. This results in undesired loss of output brightness.

**NOTE:** (2) Note that when a DMD is used with incoherent sources a filter which nearly extinguishes all wavelengths below 400 nm should be used in the illumination path to the DMD (see the individual data sheet specification). Some LEDs may not have significant spectral content below 400 nm obviating the need for a filter.

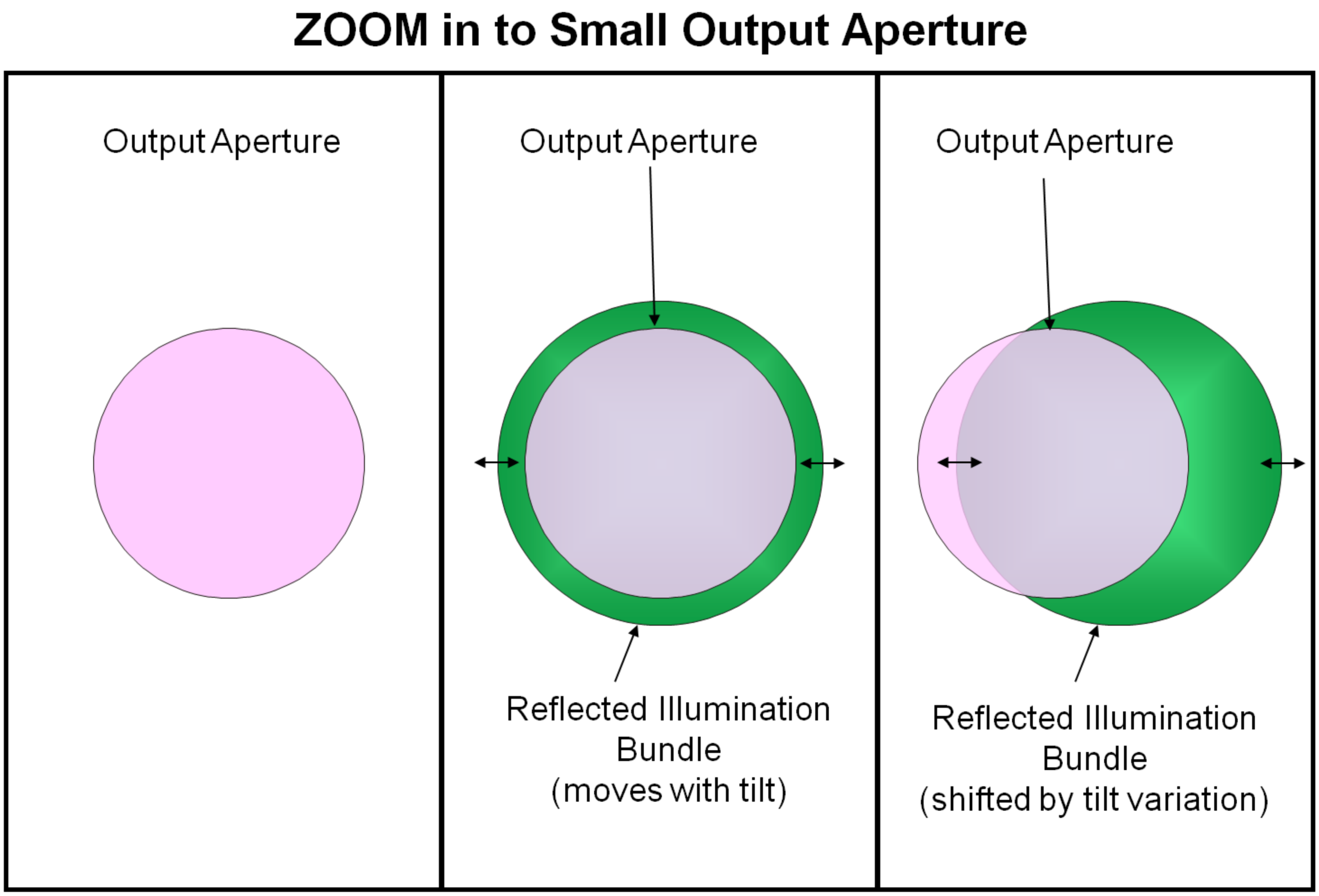


**Figure 3. Small Output Aperture**

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 4:

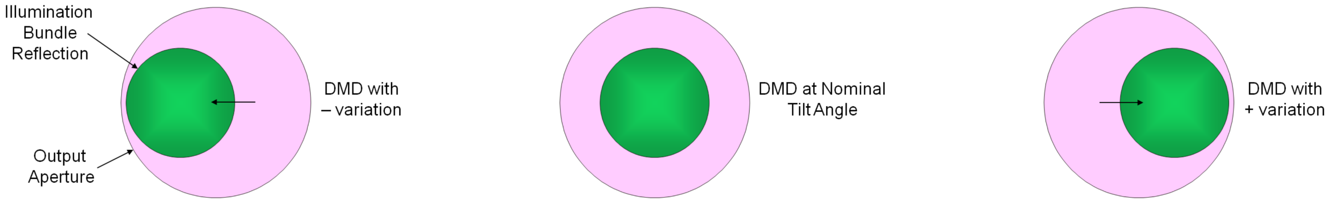


**Figure 4. Reflected Illumination Movement with Tilt Variation**

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°).

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 if the angular extent of the illumination is “vanishingly” small (mathematician talk for “nearly zero”), the aperture would have $f$/14.3 which is a cone with an angular diameter of 4°.

This in turn results in a practical limit on the de-magnification that can be reached with this tolerance. Optics with an *f* number less than one are very difficult to build. If a limit of *f*/1 is used then a de-magnification of 13x is the largest de-magnification. The graph in Figure 5 shows two curves. The magenta curve is the angular diameter of the cone at the DMD output aperture that results in an *f*/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 de-magnification.

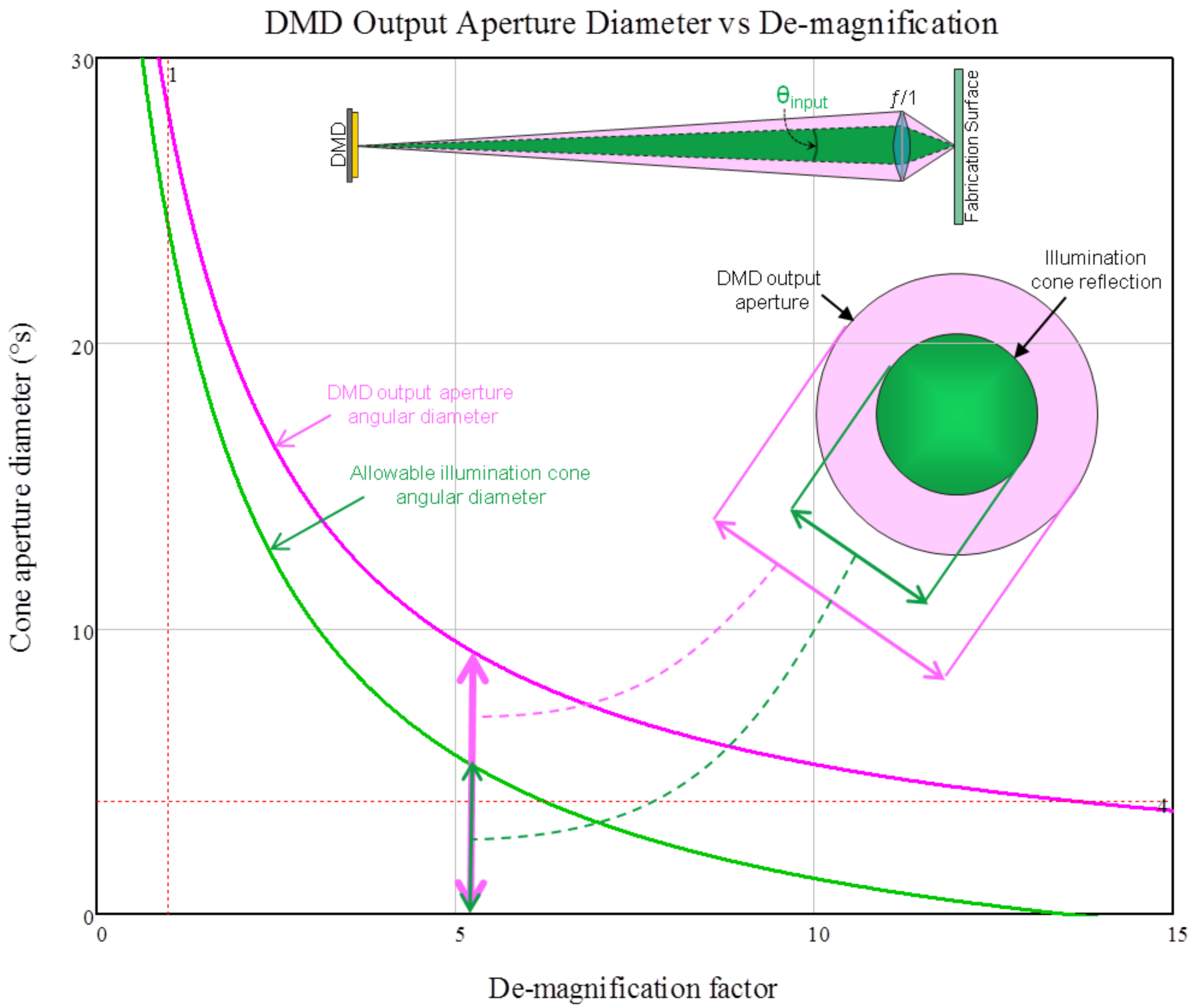


**Figure 5. DMD Output Aperture Diameter vs De-magnification**

The maximum achievable de-magnification for a given *f* number is approximately given by:

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

Where $\theta_{input}$ is the angular extent of the input illumination bundle.

In summary, incoherent sources have two limits when used in high de-magnification systems. The output is recommended to have an ƒ number less than f/14.3 and a de-magnification of 13x or less. In practice, the illumination bundle's angular diameter is several degrees so that either some aperture margin is sacrificed or a lower de-magnification chosen.

## 6.2 Coherent Sources (Lasers)

Coherent sources introduce an additional challenge. Rather than a single homogenous bundle of light the output will be restricted to "diffraction orders" as noted previously. These orders 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 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 6.

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, but if the condition is near an anti-blaze point this small aperture will only capture a fraction of the output. This is illustrated in Figure 6.

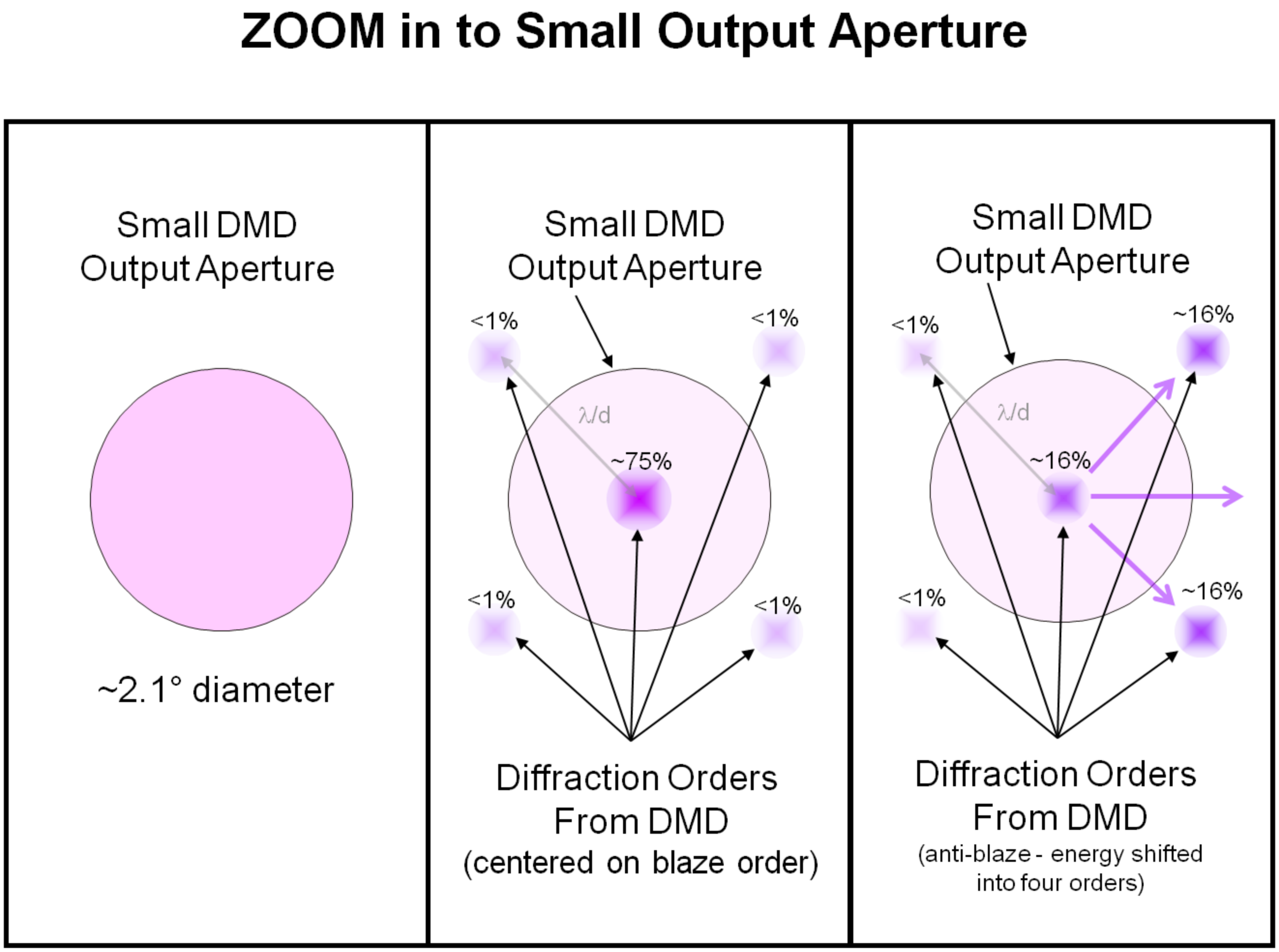


Figure 6. Diffraction Orders with Coherent Illumination

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 7. As per the example previously given, for a 7.56 µm pixel pitch DMD with collimated light at 405 nm the minimum angular diameter of about 4.4° captures one or four orders, and 6.2° captures four or five orders. The recommended minimum angular diameter is given by:

$$2 \cdot \sin^{-1}\left(\frac{\lambda}{d}\right) + \theta_{input}$$

Where $\theta_{input}$ is the angular extent of the input illumination bundle.

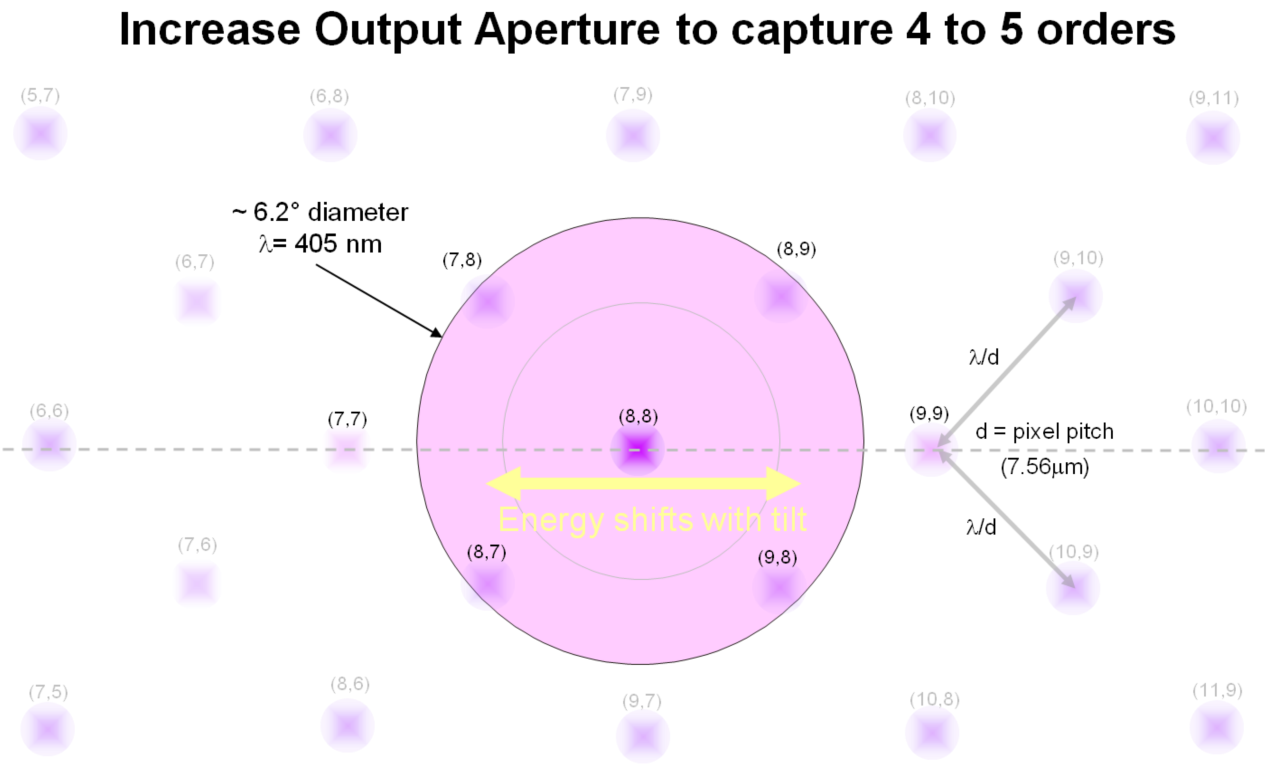


**Figure 7. Expanded Output Aperture Capturing Five Orders**

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.

As with the incoherent case, the angular diameter of the output aperture sets a practical limit on the de-magnification level that can be achieved. For example the maximum de-magnification for a 7.68 µm pixel pitch DMD using collimated light at 405 nm is about 8.4x. If the incident beam has angular extent, its diameter should be added to the output aperture before determining the de-magnification achievable.

In general the maximum de-magnification 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: $2 \bullet \sin^{-1}(\Lambda/d) + \theta_{input}$. The following formula gives an estimate of the maximum attainable de-magnification:

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

Where $\theta_{input}$ is the angular extent of the input illumination bundle.

In summary, coherent sources have the same two limits as incoherent sources. But 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 de-magnification.

## 7 Conclusion

Following the considerations outlined here will give a head start when integrating DLP technology into applications using light sources down to 400 nm. DLP technology is helping forge the way in direct imaging lithography, 3D printing, and other emerging end equipment that need higher energy photons. Let innovative DLP advanced light control propel your application into the future.

**You can learn more at the following links:**

- Getting Started with DLP Technology
- DLP High-resolution
- DLP Applications
- DLP Application Notes
- DLP White Papers

**References:**

1. Mol. Cryst. Liq. Cryst., Vol. 411, pp. 243=[1285]–253=[1295], 2004, “UV STABILITY OF HIGH BIREFIRNGENCE LIQUID CRYSTALS” – Lin, Wu, Chang and Hsu.
2. LIQUID CRYSTALS, VOL. 31, NO. 11, NOVEMBER 2004, 1479–1485, “Ultraviolet stability of liquid crystals containing cyano and isothiocyanato terminal groups” - Wen, Gauza, & Wu.

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