Application Note

System Design Considerations When Using TI DLP® Technology Down to 400nm

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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 considerations for using TI DLP® Digital Micromirror Devices [DMD] that are specified to operate down to 400 nm.

Table of Contents

List of Figures

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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 photon energy is given by E= (hc/λ) where h is Plank's constant, c is the speed of light, and λ is the wavelength of light.

This equation shows that photon 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.

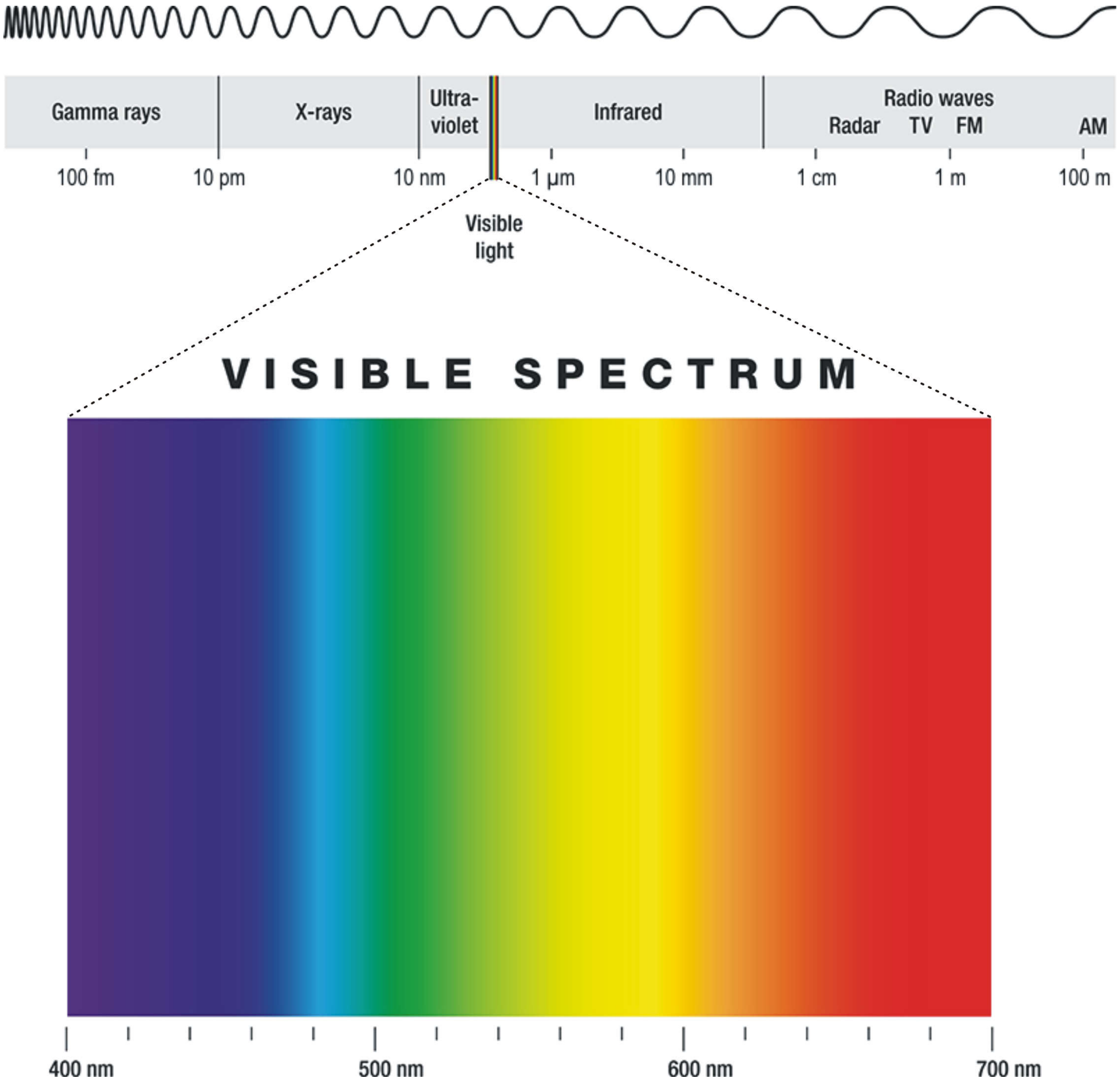

Figure 1-1. Visible Spectrum portion of the Electromagentic Spectrum

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Note

Higher engergy is shown from the left down to lower energy on the right.

Examples of applications that benefit from higher photon 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. Typically photoresist and resin materials are more reactive to higher photon energy resulting in faster cure rates.

Remarkable design techniques are implemented in Digital Micromirror Devices [DMD] specified to operate down to 400 nm. Examples are the DLP7000BFLP, DLP9500BFLN, DLP6500BFLQ, DLP9000BFLS and DLP9000XBFLS. In particular 405 nm light can be used with this type of DMD. Light Emitting Diodes [LED] and laser diodes at this wavelength are now readily available at reasonable cost, making the 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 (higher energy photons) than other 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]

However the higher energy of shorter wavelength photons that are an excellent choice for lithography and 3D print systems requires greater attention to design considerations when used with a DMD, Important design considerations are explored in this application note.

2 Thermal Considerations

Although Type A DMD devices are capable of operating at shorter wavelengths, these devices are not completely impervious to the effects. DMD array temperature becomes an important factor when operating in the deep blue portion of the spectrum down to 400nm.

Keeping DMD array temperatures below 30° C with 20° to 25° C is preferred which can be accomplished with passive or even active cooling such as a thermo electric cooler [TEC]. For Type A DMDs, care needs to 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 promotes best performance of the DMD when used with higher energy photons.

TI has an excellent application note *Digital Micromirror Device Thermal Considerations Including Pulsed Optical Sources, application note* that covers in great detail general thermal considerations for DMDs.

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 and in higher temperature operations. 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 duty cycle.

Duty cycle for DMDs 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 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 this is operated at 50/50 in quiescent periods, the closer the overall average is to 50/50.

Note

Shutter (or turn off) illumination 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, instead shutter at the source, such as a mechanical 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 at 38/62 for four hours during quiescent periods averages to 50/50(2) .

Note

The 50/50 average is an oversimplification since during operation when being illuminated heats the pixels, whereas operation when the illumination is off cools the pixels. For high fluence systems, experimentation needs to be done to determine how much longer to run the reciprocal duty cycle or how much to weight the reciprocal to restore the residual tilt to flat.

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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 can 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 400nm this tilt angle difference is such that customers can receive a DMD that results in any condition from anti-blazed to blazed. Therefore, the system output optics needs to have sufficient aperture to collect, at the very least, the four brightest orders in an anti-blaze condition. For example, at 405nm, a 7.56µm 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.

An illumination adjustment mechanism is further recommended 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 allows the brightest orders to be moved into the output aperture in wavelengths near 405nm

5 Optical Considerations

In systems with one-to-one or greater magnification, designing illumination and output optics with f numbers as small as $f/2.4$ are practical and desirable, since slightly under-filling the output pupil provides tilt variation tolerance in an optical system. For example, illuminating with $f/3$ into an $f/2.4$ output allows the image of the illumination pupil to remain within the output aperture with tilt angle variations.

General DLP optical system considerations are discussed in the tool DLP®Optical Design Guidlines . The following sections of this application note 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 6-1.

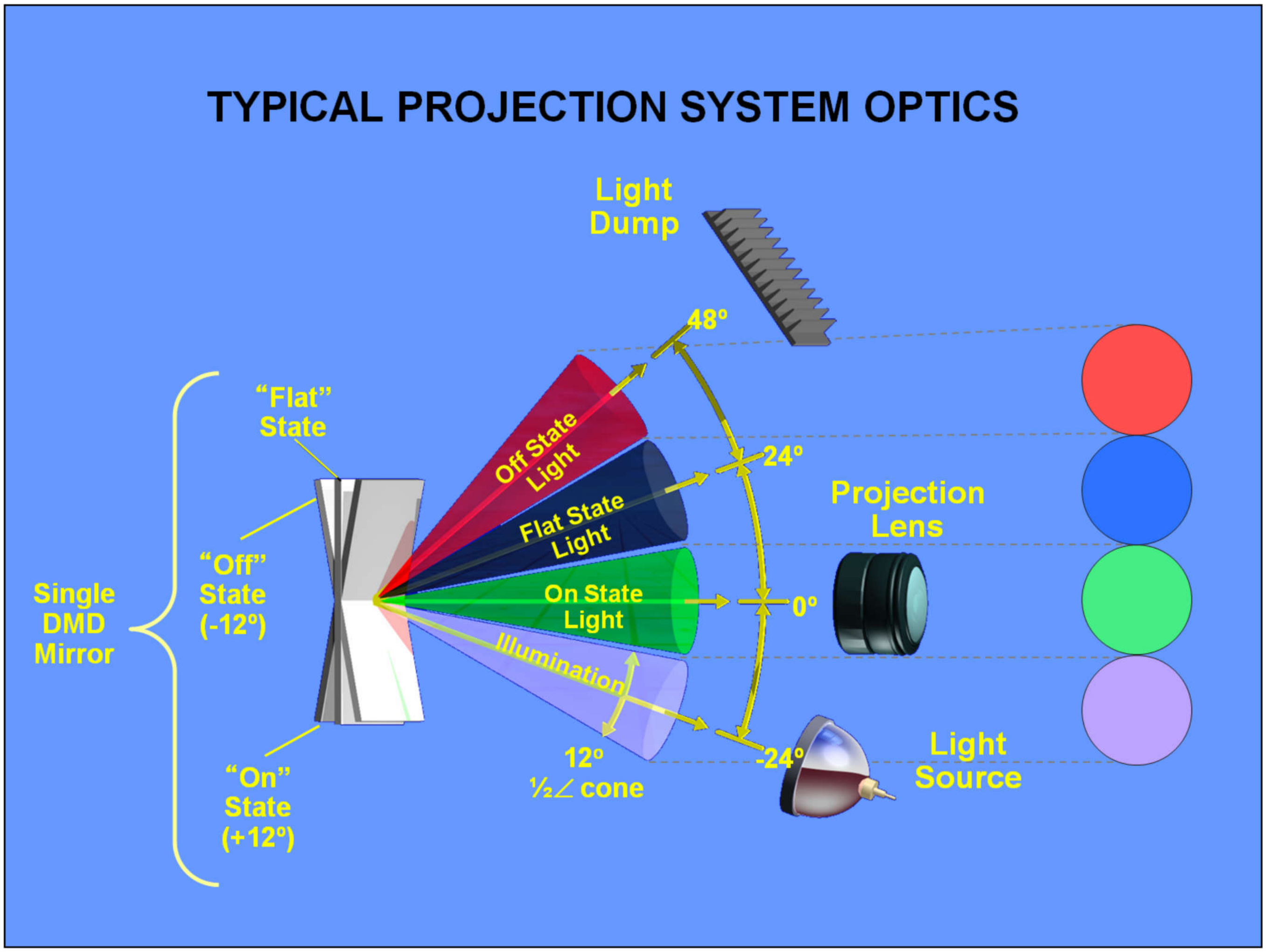

Figure 6-1. Typical Projection System Optics

However, some lithography and 3D print systems can use de-magnification of the DMD array image to address very small features as small as 1µm. Figure 6-2 shows the small size of the output aperture of such systems relative to a traditional projection optical system.

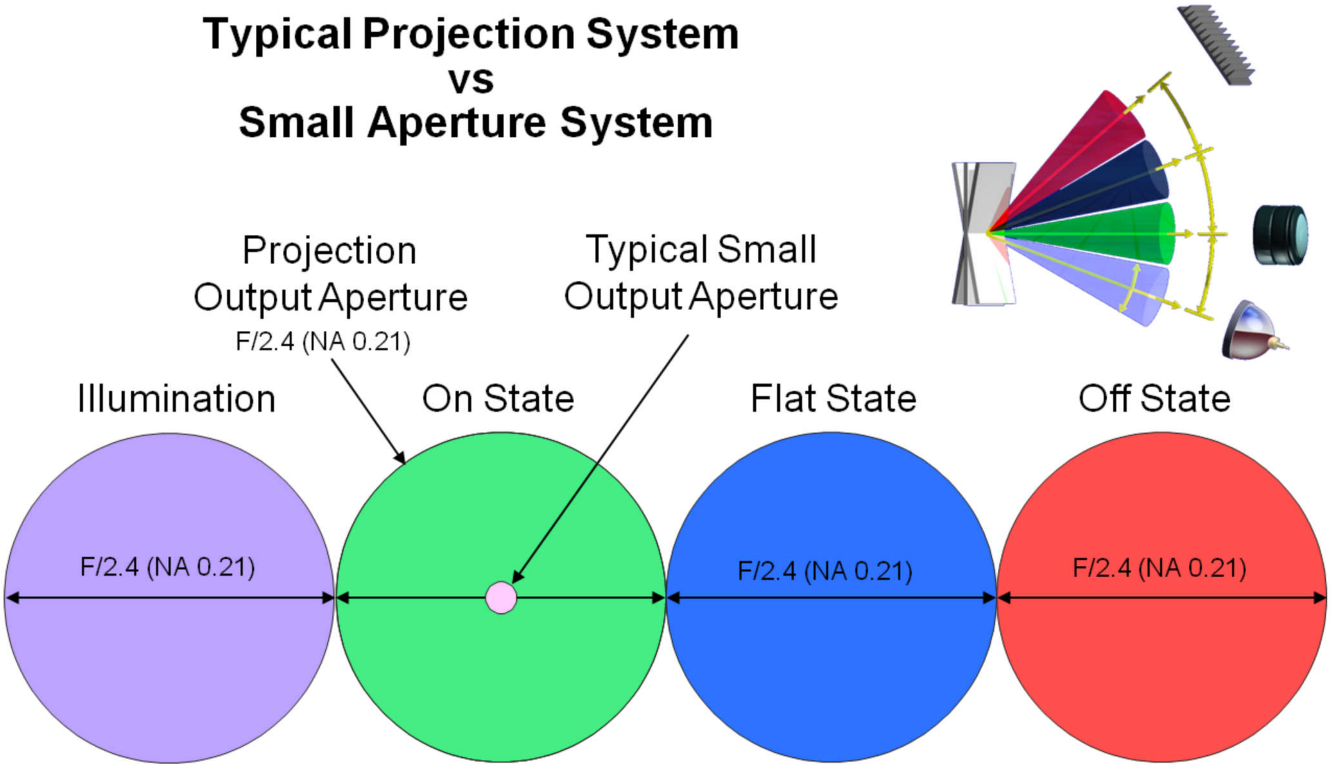

Figure 6-2. Light Distribution at Projection Lens Entrance Pupil

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 that match the size of the illumination bundle (cone of light) to the DMD output bundle, the micromirror tilt variations can allow some light to spill off of the side or not completely fill the output aperture as shown in Figure 6-3. This results in undesired loss of output brightness.

Note

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

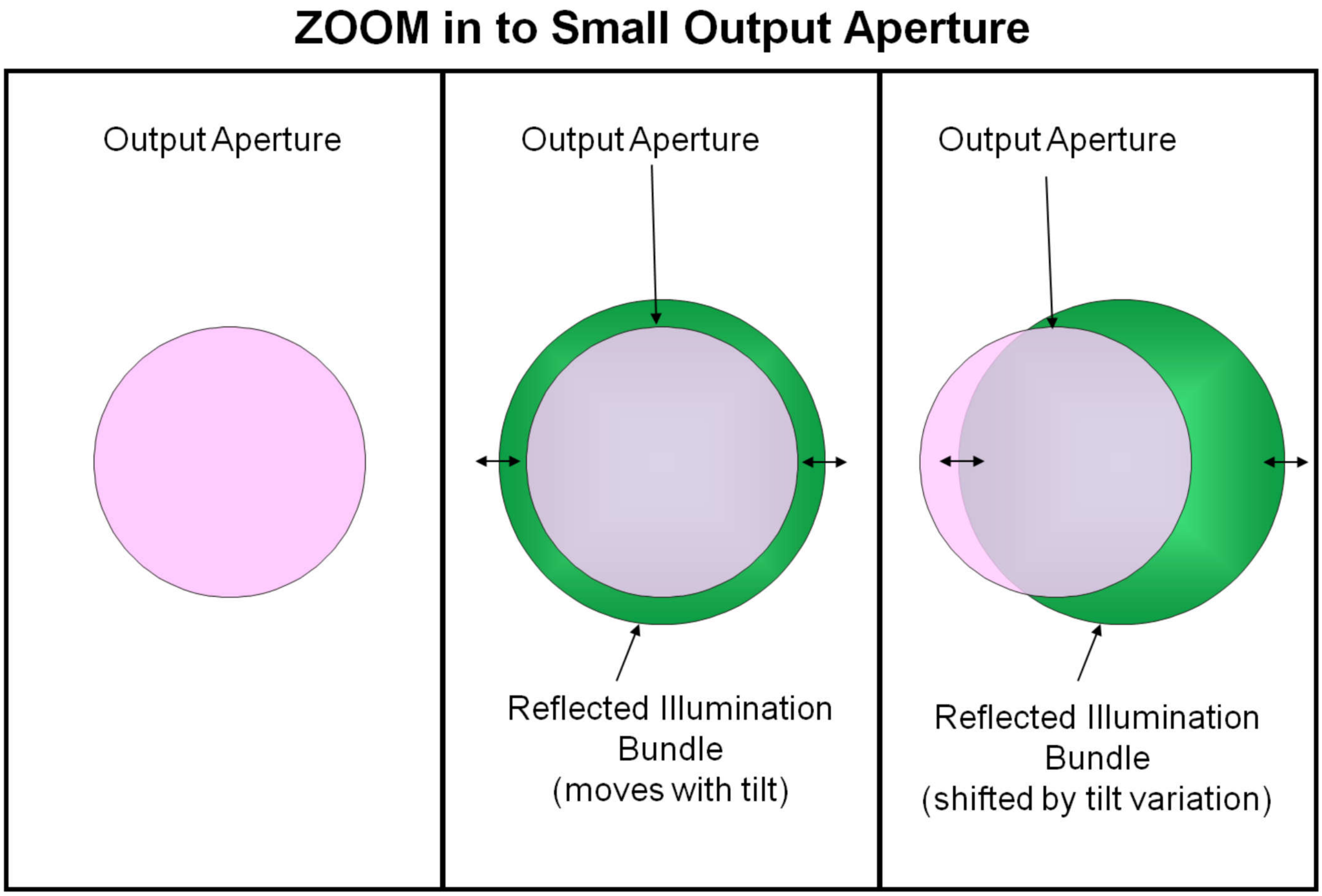

Figure 6-3. Small Output Aperture

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 6-4:

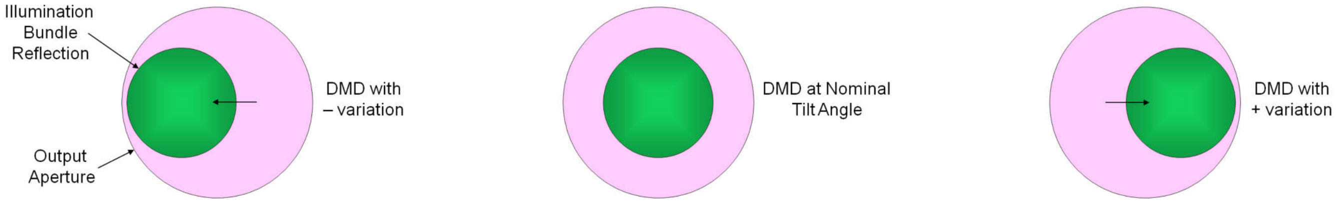

Figure 6-4. Reflected Illumination Movement with Tilt Variation

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 angular 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 4° of tolerance. Even if the angular extent numerical aperture (NA) of the illumination is very small, the aperture has an $f/14.3$ equivalent which is a cone with an angular diameter of 4°.

A practical limit exits for the de-magnification that can be reached within 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 6-5 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.

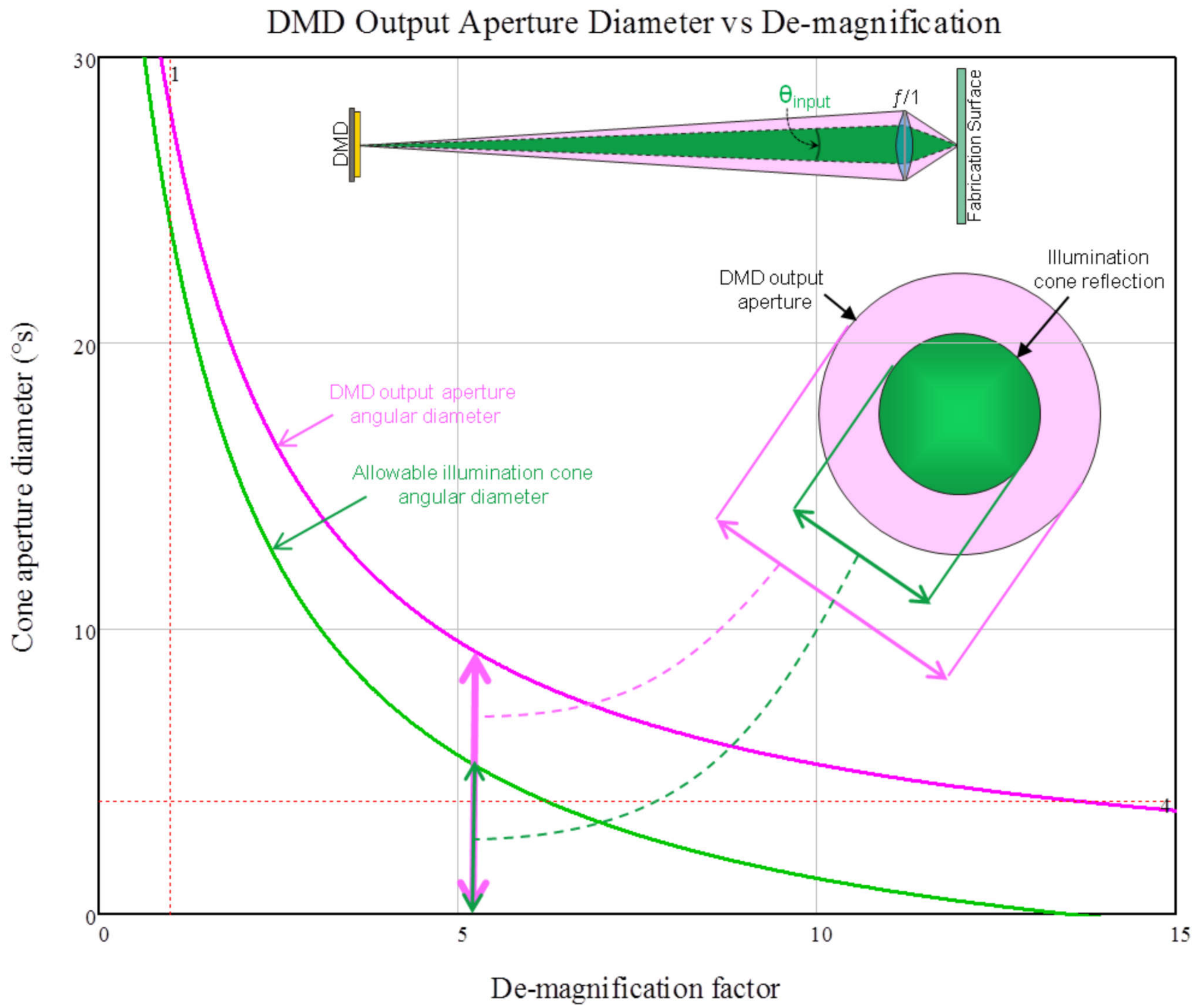

Figure 6-5. DMD Output Aperture Diameter vs De-magnification

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 θ_{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 f number less than f/14.3 and a de-magnification of 13x or less. In practice, the illumination bundle angular diameter needs to be kept at several degrees, allowing either some aperture margin to be recovered or a lower de-magnification to be chosen.

6.2 Coherent Sources (Lasers)

Coherent sources introduce an additional challenge. Rather than a single homogenous bundle of light, the output is 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 *sees* 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 this 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, then 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, then most of the energy available is captured in this one order, but if the condition is near an anti-blaze point this small aperture only captures a fraction of the output. This is illustrated in Figure 6-6.

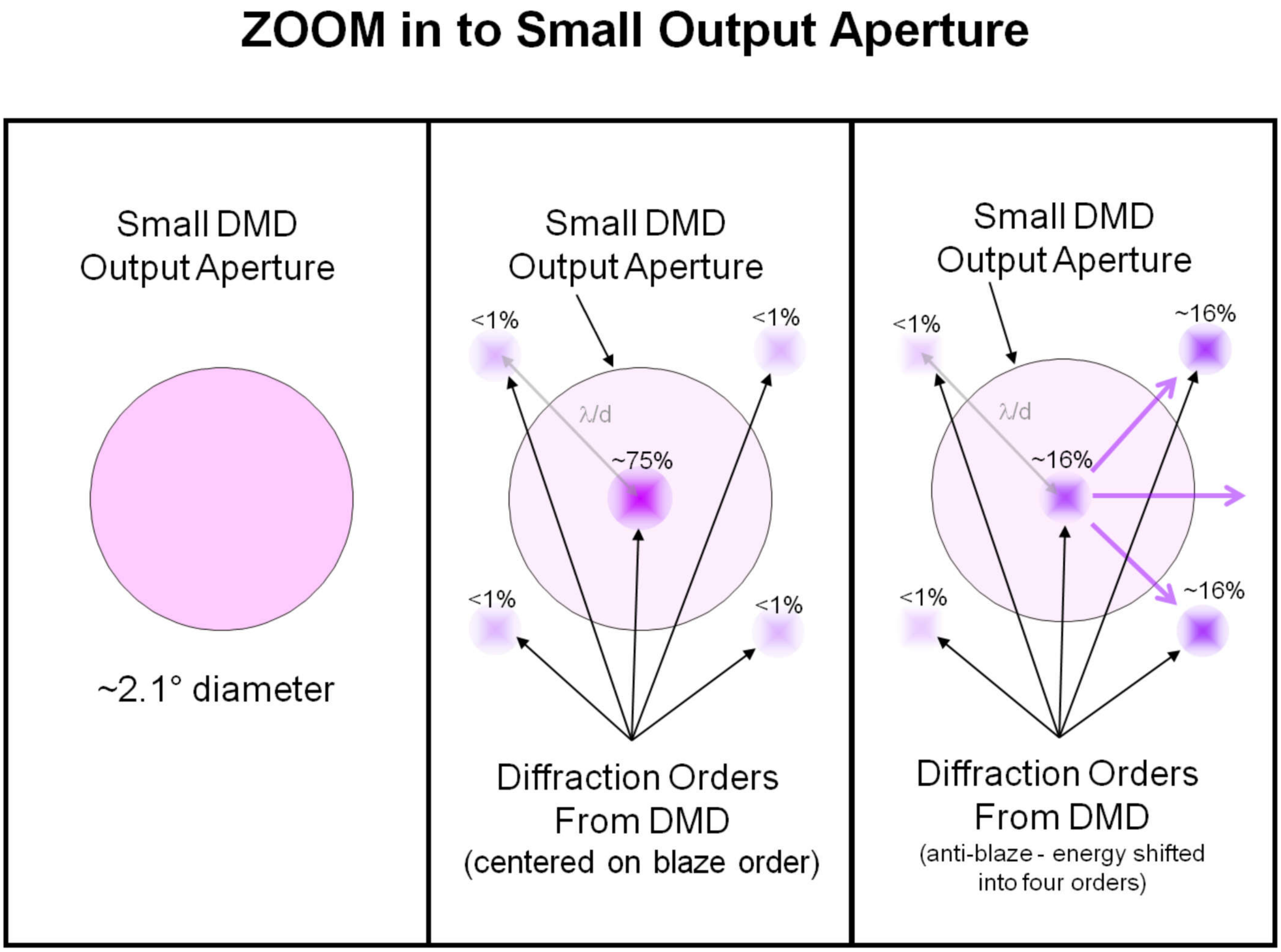

Figure 6-6. Diffraction Orders with Coherent Illumination

To provide tolerance in the system design, TI recommends that the output aperture be expanded to capture four to five orders as shown in Figure 6-7. As per the example previously given, for a 7.56μm 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:

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

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

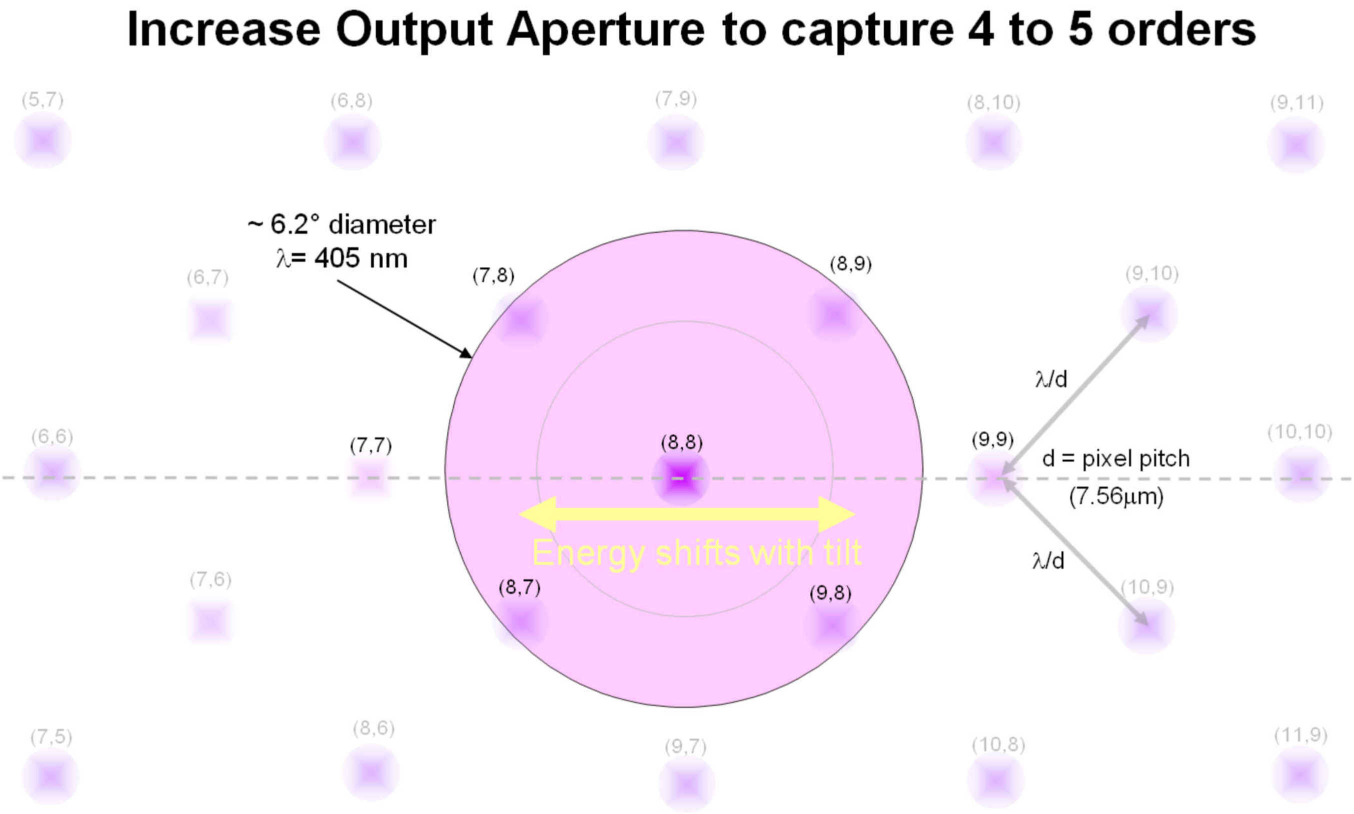

Figure 6-7. Expanded Output Aperture Capturing Five Orders

Although the orders do not move with variations in tilt angle, the orders do move with changes in the illumination angle. If the illumination is moved by an angle of θ, then the orders at the output move by approximately -θ. Therefore, TI recommends 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 7.68µm pixel pitch DMD using collimated light at 405 nm is about 8.3x. If the incident beam has angular extent, then the diameter needs to 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: $2\cdot\sin^{-1}(\lambda/d) + \theta_{input}$. 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 θ_{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 Summary

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

8 References

- Texas Instruments, Getting Started with DLP Technology
- Texas Instruments, Digital Micromirror Device Thermal Considerations Including Pulsed Optical Sources , application note
- Texas Instruments, Using Lasers with DLP® DMD Technology , application note
- Texas Instruments, DLP® Optical Design Guidlines
- Mol. Cryst. Liq. Cryst., Vol. 411, pp. 243=[1285]–253=[1295], 2004, “UV STABILITY OF HIGH BIREFIRNGENCE LIQUID CRYSTALS” – Lin, Wu, Chang and Hsu.
- LIQUID CRYSTALS, VOL. 31, NO. 11, NOVEMBER 2004, 1479–1485, “Ultraviolet stability of liquid crystals containing cyano and isothiocyanato terminal groups” - Wen, Gauza, & Wu.

9 Revision History

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

Changes from Revision * (November 2014) to Revision A (August 2025)	Page
• Updated Abstract	1
• Added the DLP7000FLP, DLP9500FLN, and DLP9000XFLS DMDs to the list of Type A DMD examples	2
• Specified that the discussion applies to Type A DMDs	3
• Added note about idle duty cycle operation to restore residual tilt to near flat	3
• Updated link to Optical Design Guidlines	4
• Added clarify that the discussion applies to Type A DMDs	6

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