Optical Design Guidelines for DLP® products

Revision B

July 27, 2023

Topics

- Introduction to DLP Technology
- DMD Optical Properties
- Projection Architecture and Design
  - Light Source Illuminator System Design
  - Illumination Relay Design
  - Projection Lens Considerations
- Resolution Enhancement
- Colorimetry & Systems Lumens Budgeting

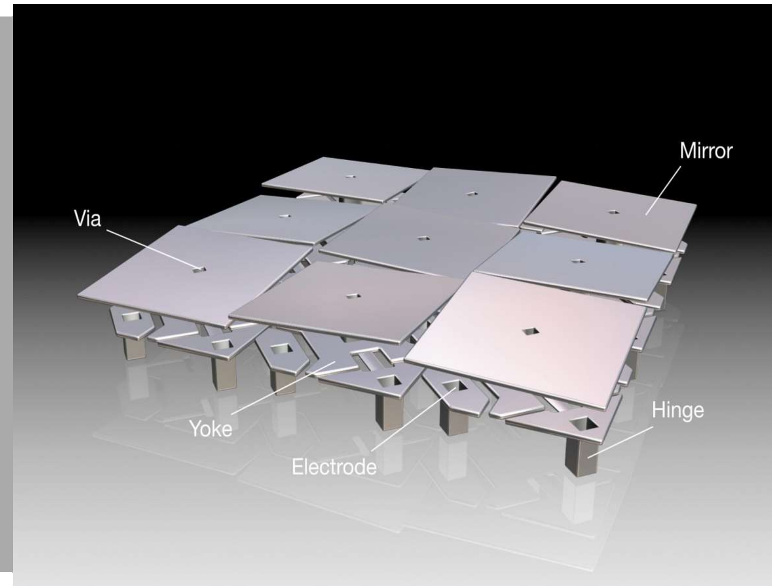
Introduction to DLP Technology

For more information, refer to application report "Getting Started With TI DLP® Display Technology"
https://www.ti.com/lit/pdf/dlpa059

DLP Technology: Millions of Mirrors

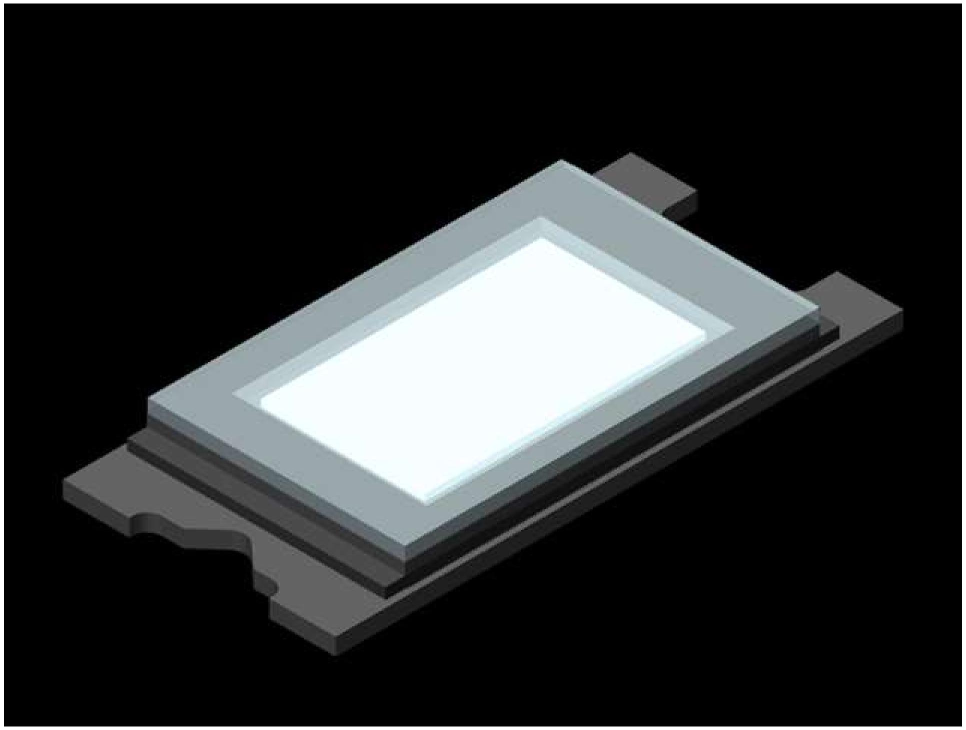
The industry leader in:

Digital Cinema, Projection, and MEMS

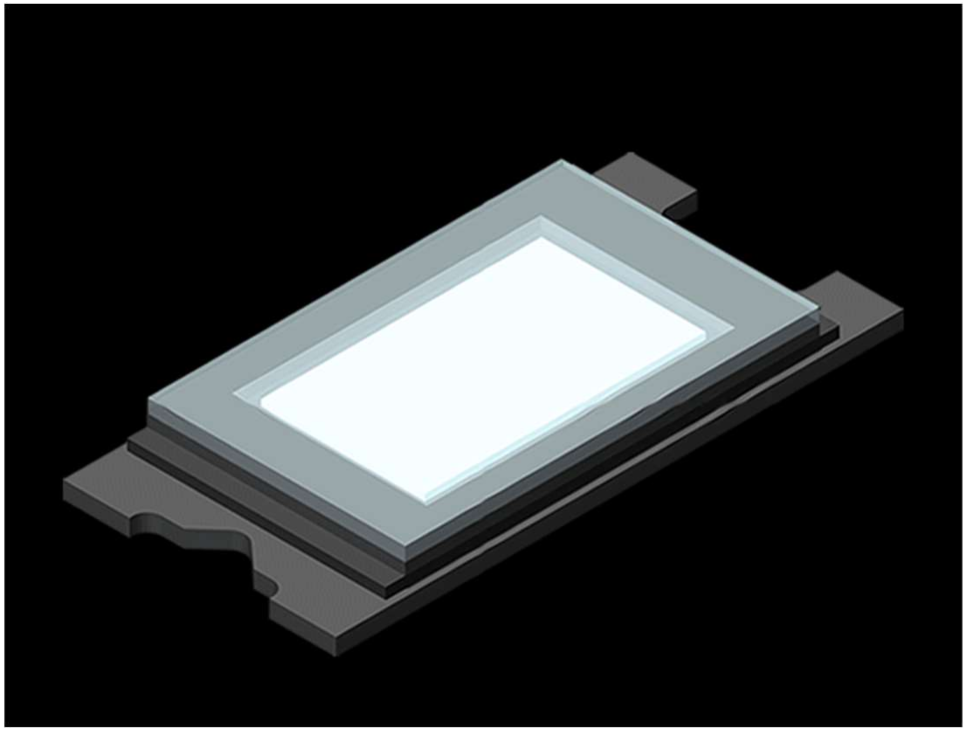


Extremely Flexible and Programmable Light Management

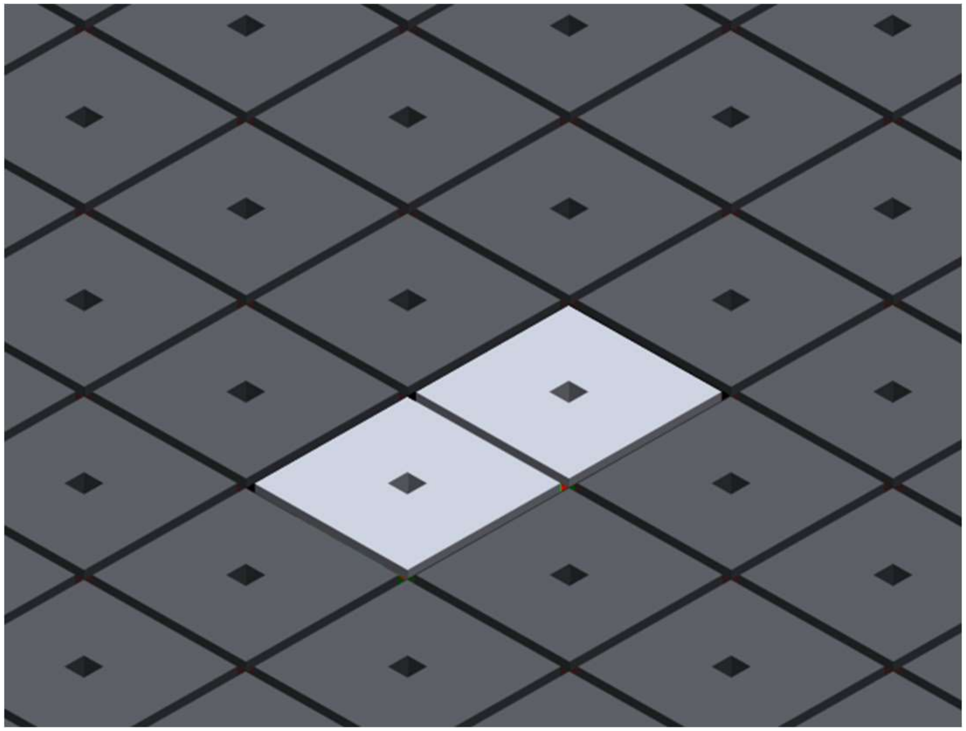
How DLP Technology Works



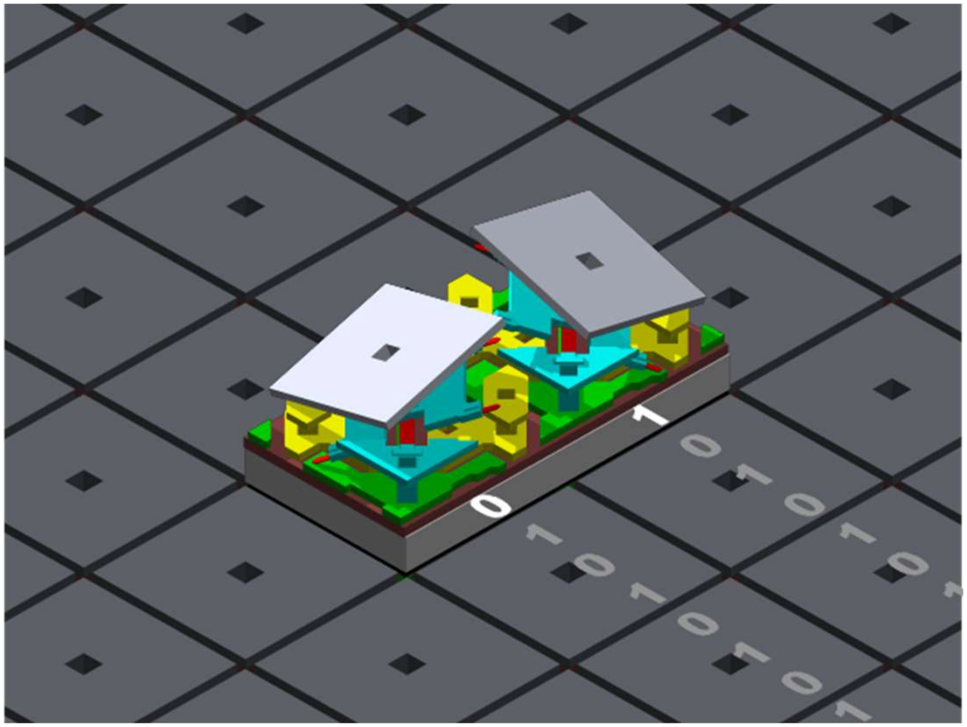
How DLP Technology Works



How DLP Technology Works



How DLP Technology Works



How DLP Technology Works

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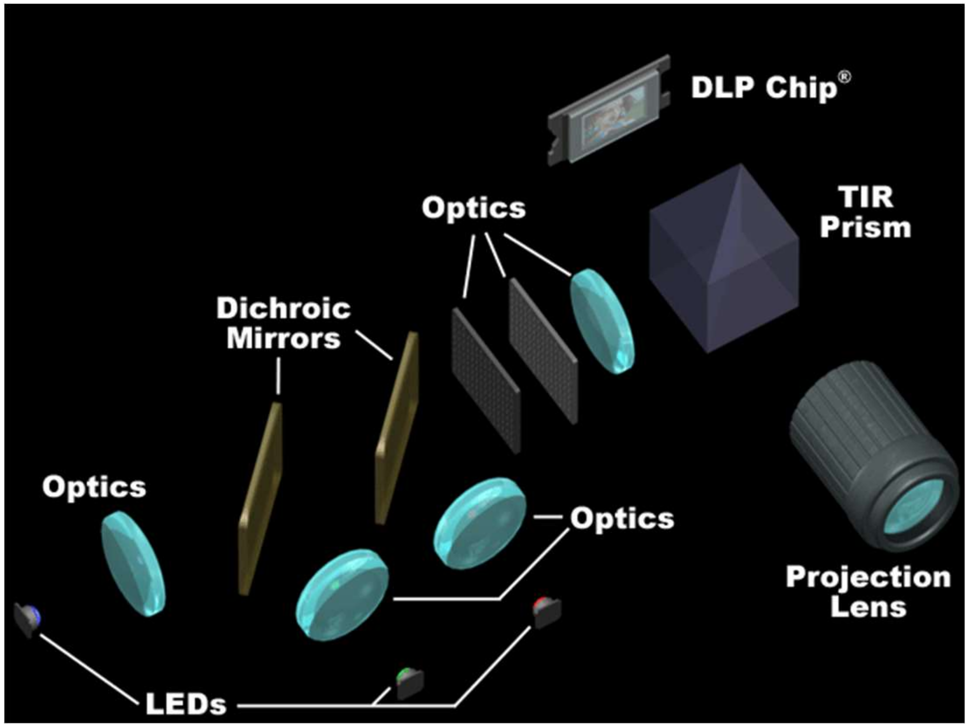
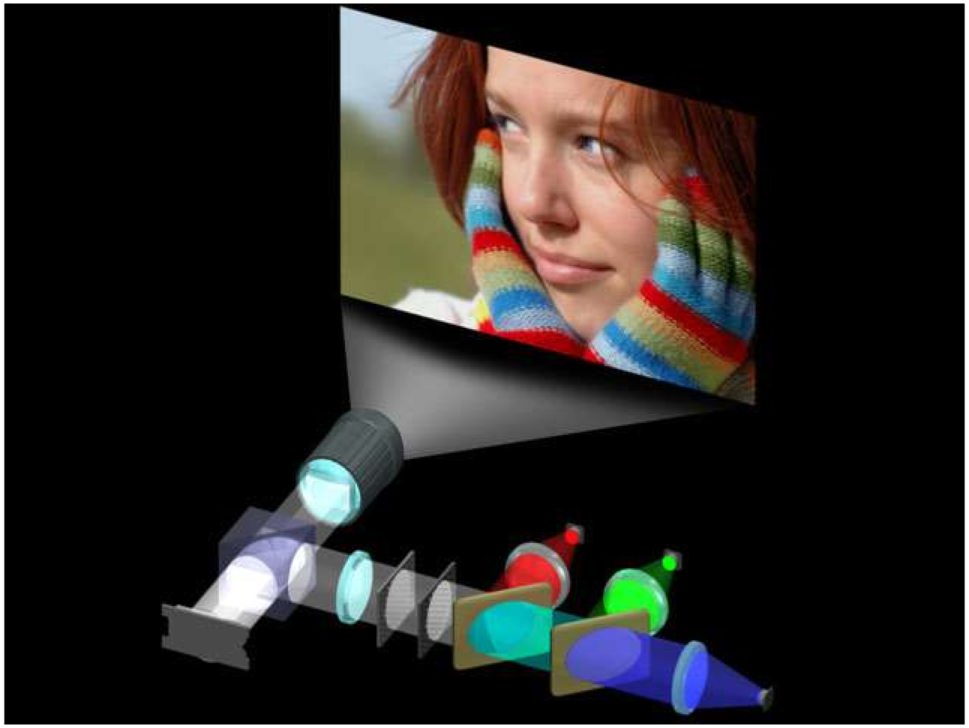


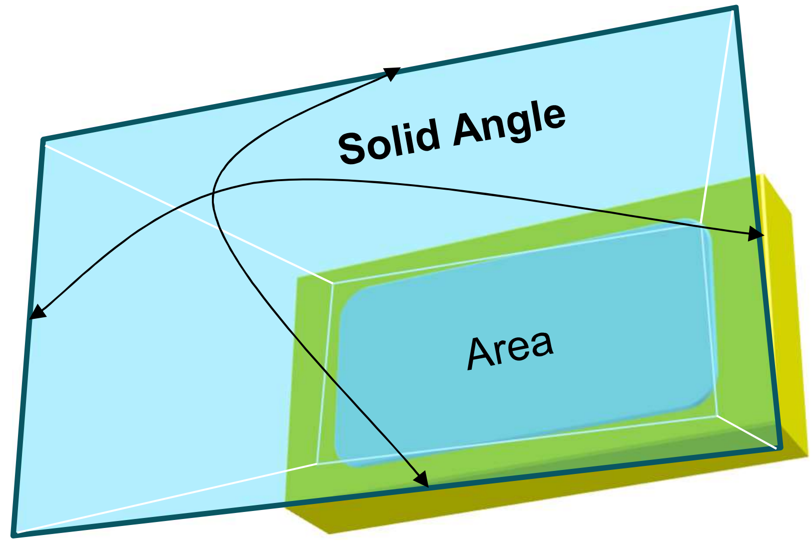
How DLP Technology Works



Digital Micromirror Devices (DMD) Optical Properties

Etendue - Important concept

- Quantifies how much space the light takes up spatially and angularly
- Measure of system throughput capability
  - Sometimes called “extent” or “invariant”
  - Throughput limited by element with smallest etendue
- DMD Etendue
  - Solid angle limited by mirror tilt angle
  - Smaller DMD diagonal = smaller area
  - Small Etendue makes it more difficult to couple light

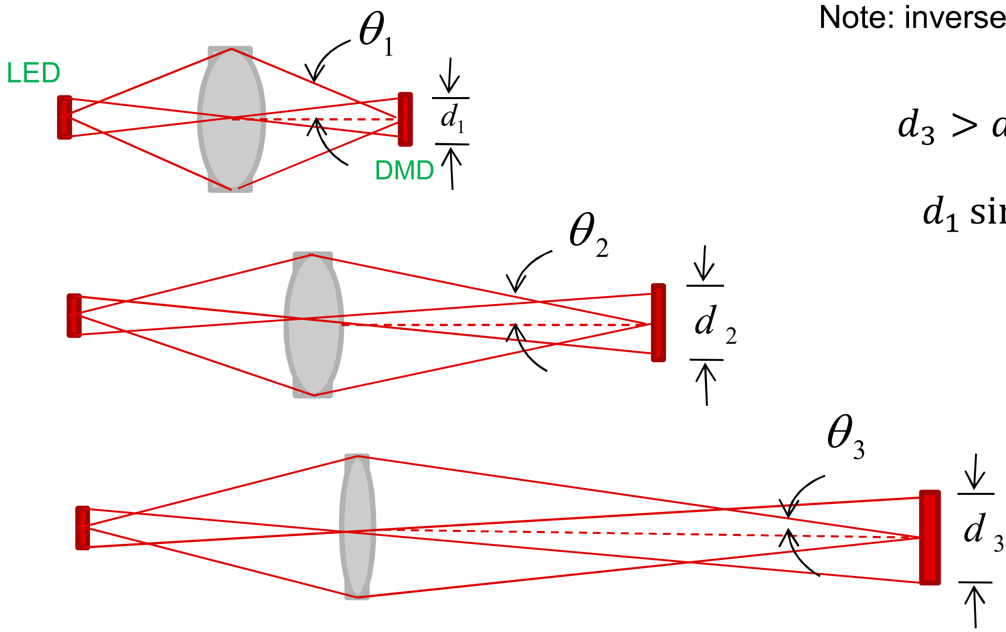


Practical definition:

$$Etendue \cong \pi \times Area \times \sin^2\theta$$
$$Etendue \cong Area \times Solid\ Angle$$

For more information, visit: https://training.ti.com/etendue-how-brief-introduction-etendue-projection-systems

Etendue: LED source illustration



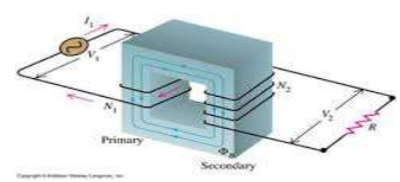
Note: inverse relationship between beam size and beam angle

$d_3 > d_2 > d_1$ and $\theta_1 > \theta_2 > \theta_3$ but…

$$d_1 \sin\theta_1 = d_2 \sin\theta_2 = d_3 \sin\theta_3 = constant$$

Constant depends on source Etendue

Electrical transformer analogy:
Power (constant) = current x voltage
Etendue (constant) = area x tilt angle

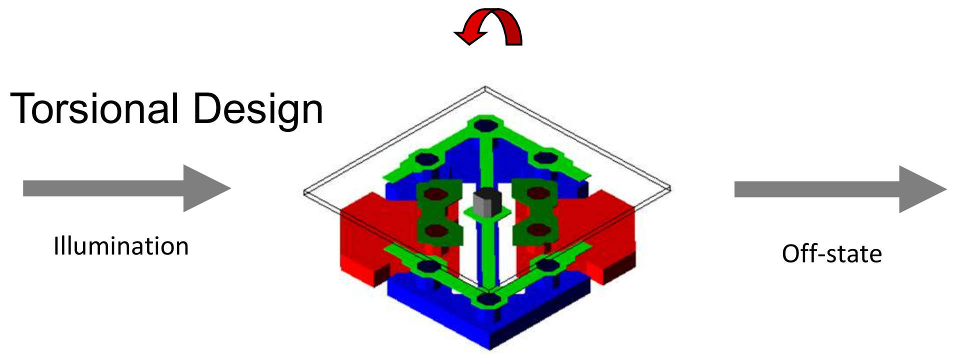


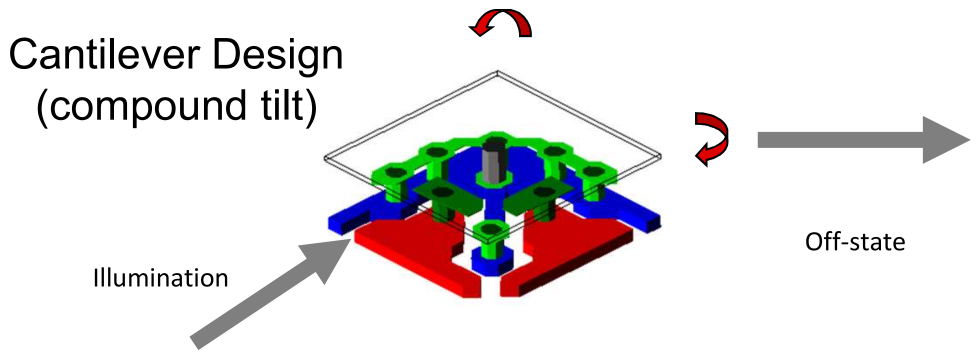
Cantilever vs Torsional Pixel

DLP types of pixels:
- FTP: fast-track pixel, 13.68 um pitch
- SPD: small-pixel development, 10.8 um pitch
- HEP: high-efficiency pixel, 9.0 um pitch
- VSP: voltage-scale pixel, 7.56 um pitch
- TRP: tilt-and-roll pixel, 5.4 um pitch
- SST: single spring tip, 5.4 um pitch
- RDP: resolution density pixel, 4.5 um pitch

Torsional pixel designs
- FTP, SPD, HEP, VSP, SST, RDP
- Illumination direction is toward a corner of the pixel
- 12° and 14.5° tilt depending on device/ pixel (refer to datasheet)

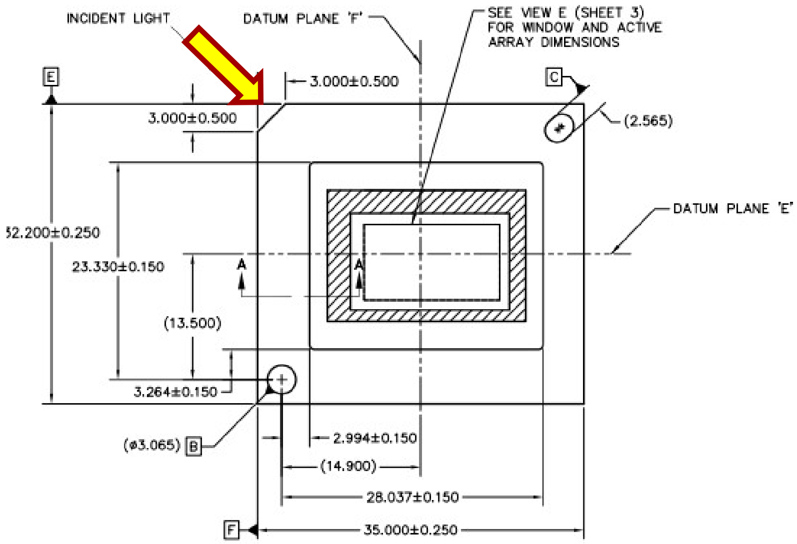
Cantilever pixel design
- TRP
- Illumination direction is orthogonal to a pixel side
- 17° effective tilt (refer to datasheet)



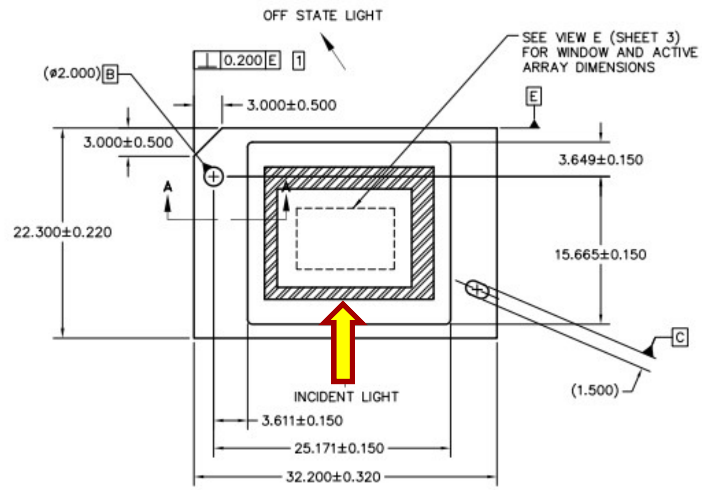


Corner vs. Bottom Illumination

Example: DLP650NE (VSP pixel)



Example: DLP480RE (TRP pixel)



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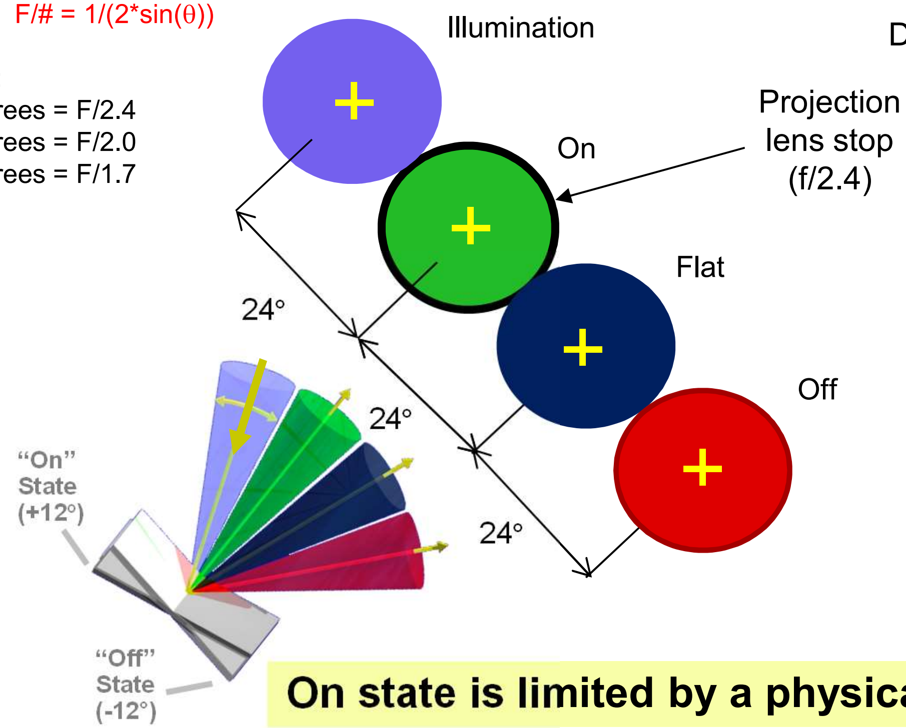
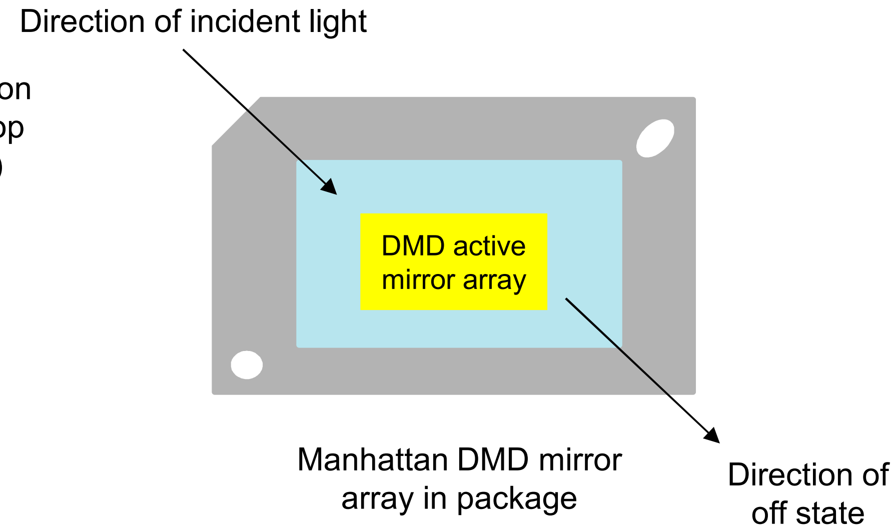
Corner Manhattan DMD Illumination Example

Angular size of on state is the F/#

F/# = 1/(2*sin(θ))

Example:
12.0 degrees = F/2.4
14.5 degrees = F/2.0
17.0 degrees = F/1.7



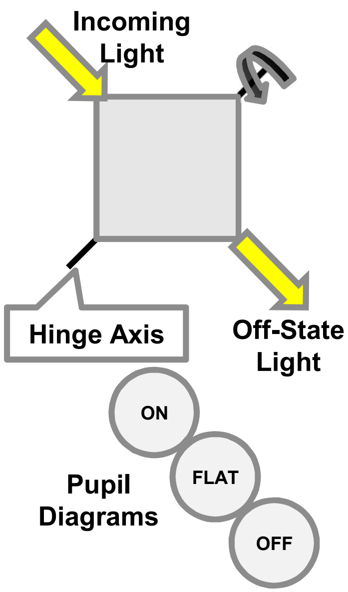


On state is limited by a physical aperture in the projection lens (STOP)

**DMD mirror does not have a flat state. Flat state is referred to as flat optical surface Fresnel reflections (i.e. DMD window, prism, etc.) that may enter the projection pupil and impact system contrast.*

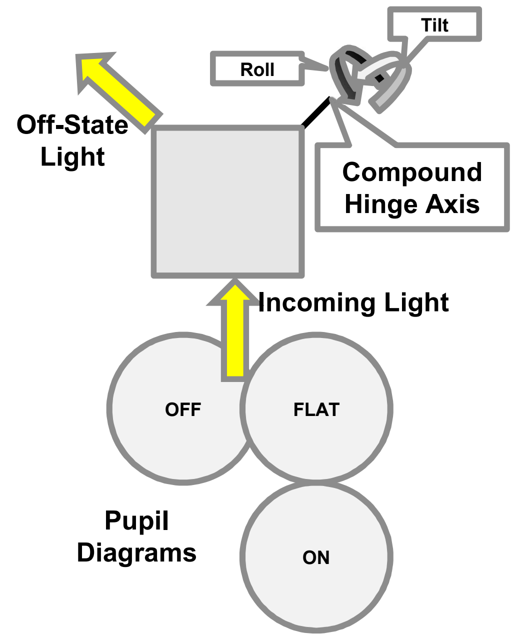
Pupil locations for Pixel Architectures

Torsional – Corner Illuminated



- Limited to symmetric f/2.4 (for 12° pixel) or F/2.0 (for 14.5° pixel) max due to flat state overlap
    - Overdrive possible at expense of contrast loss.
- 24° illumination angle; 12° pixel tilt angle
- 29° illumination angle; 14.5° pixel tilt angle

Cantilever – Bottom Illuminated

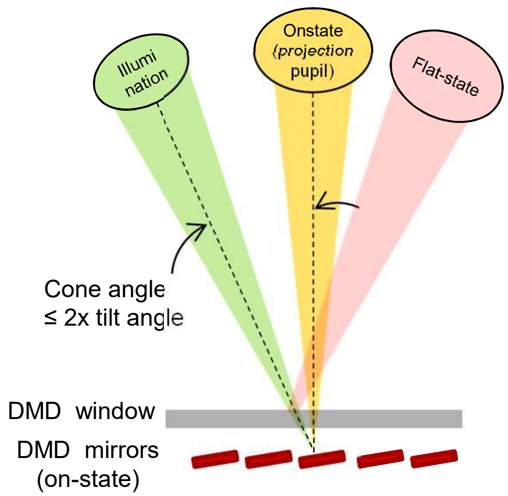


- Symmetric Expansion up to f/1.7 = 2X etendue vs. f/2.4
    - Overdrive possible at expense of contrast loss
        - not recommend faster than F/1.5
- 34° degree illumination angle; 17° pixel tilt angle

Matching Source Etendue with DMD

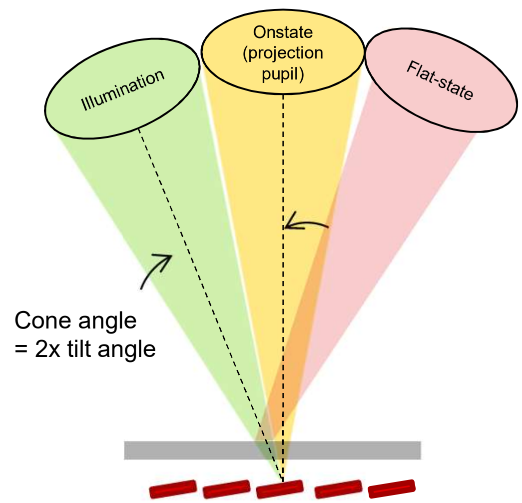
Source Etendue<DMD

- Small etendue sources (i.e. laser)
- System capable of high contrast



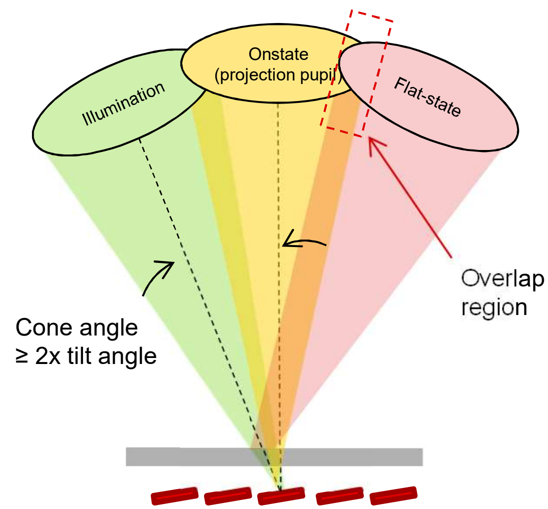
Source Etendue=DMD

- Matched source and DMD Etendue
- Some separation between illumination and projection
- Best tradeoff between brightness and contrast (usually)



Source Etendue>DMD

- Large Etendue sources (i.e. high brightness LEDs)
- Can increase illumination angle to prevent interference with projection pupil
- “Overdrive” condition allows illum & proj pupil overlap
- Increase brightness at expense of reducing contrast
- Apertures recommended to block flat state light



LED matching to DMD Example

- 0.47" TRP DMD
  - 10.368mm x 5.184mm
  - 17° Mirror Tilt

$$Etendue = \pi * Area * \sin(\theta)^2$$
$$= \pi * 10.368 * 5.184 * \sin(17°)^2$$
$$= 14.43\ mm^2 sr$$

Break up Etendue in X and Y dimensions ("optical invariant")

DMD

$$E_{x_{DMD}} = X_{DMD} * sin_x(\theta) = 10.368 * sin_x(17°) = 3.03$$

$$E_{y_{DMD}} = Y_{DMD} * sin_y(\theta) = 5.184 * sin_y(17°) = 1.52$$

Note: overfill & anamorphism not included in these example calculations

LED (Lambertian ±90° emission)

$$E_{x_{DMD}} = E_{x_{LED}} = 1.52 = X_{LED} * sin_x(\theta) = X_{LED} * sin_x(90°) \rightarrow X_{LED} = 3.03$$

$$E_{y_{DMD}} = E_{y_{LED}} = 0.85 = Y_{LED} * sin_y(\theta) = Y_{LED} * sin_y(90°) \rightarrow Y_{LED} = 1.52$$

DMD Efficiency

Example: 7.6µm pixel with f/2.4 optics

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

Where

$transmission_{window}$	is window transmission including four anti-reflection surfaces
$reflectivity_{mirror}$	is the mirror reflectivity
$efficiency_{diffraction}$	is the mirror array photopic diffraction efficiency into a given F/#
$efficiency_{fillfactor}$	is the fractional mirror coverage (on-state mirrors) projected in the direction of the illumination

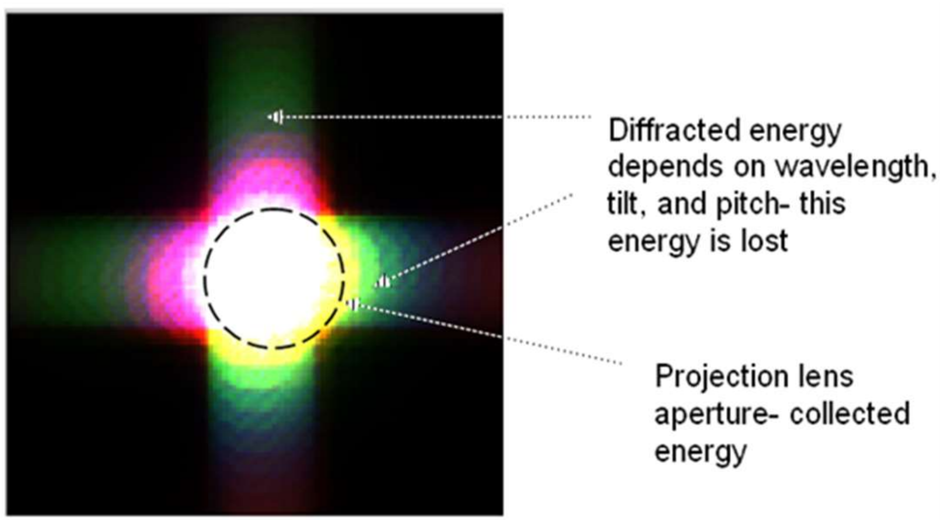
It should be noted that the first three factors depend on wavelength so more accurate results are obtained by calculating efficiency as a function of color and f/#

DMD efficiency = 0.96 × 0.89 × 0.84 × 0.93 = 0.67

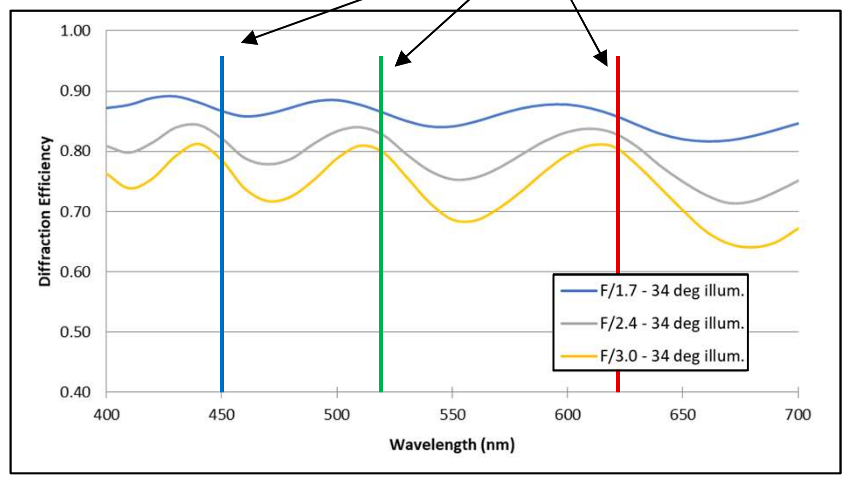
For more information, refer to application note "DMD Optical Efficiency for Visible Wavelengths" https://www.ti.com/lit/pdf/dlpa083

What is Diffraction Efficiency?

- DMD diffracted energy is reflected scattered light due to the periodic structure of the DMD micromirror array – similar to a grating
- Diffraction efficiency is a measure of the amount of light in the ON-STATE that enters the projection lens aperture (F/#)
- Higher order energy is scattered beyond the projection lens aperture and lost



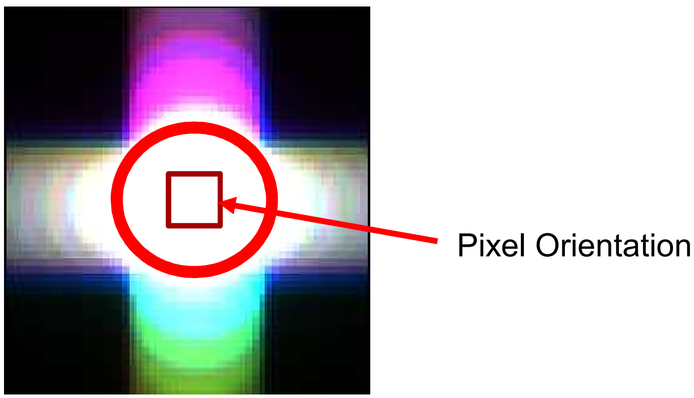
Typical RGB light source wavelength peaks



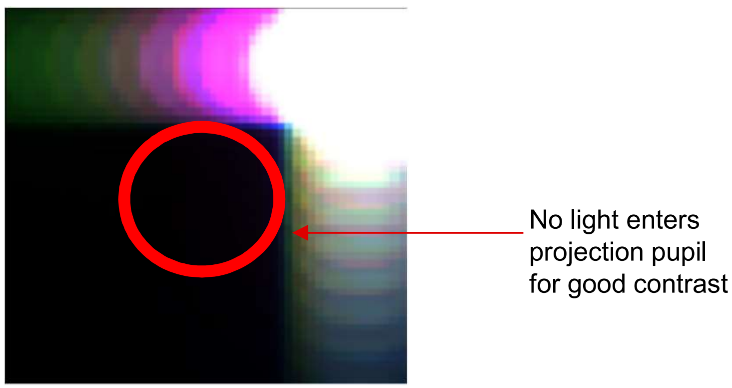
5.4µm Pitch DMD Mirror Calculated Diffraction Efficiency

DMD (system) Contrast

- Limited by collection of diffracted light into projection lens entrance pupil
- Strong linear relationship in system F/# for matched illumination and projection lens pupils
- Contrast generally increases with illumination angle
- Contrast decreases with increased stray light in projection path



On-state pupil with DMD in on-state (exaggerated)



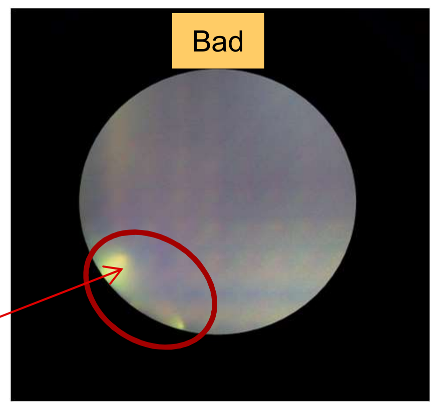
On-state pupil with DMD in off-state (exaggerated)

Additional DMD (system) Contrast Notes

- Contrast is limited by scatter from the mirror array (previous slide)
- Projection system F/# affects contrast (higher is better)
  - Higher F/# increases contrast (but lets less light through)
  - Must match illumination and projection lens f/# to achieve maximum contrast
- Illumination incidence angle affects contrast
  - Higher incidence angle (> 2x Pixel Tilt) increases contrast but lowers light throughput
- Flat state light entering the projection lens pupil will significantly degrade contrast
- Good control of stray light is needed to maximize contrast
  - Examples: Lens edge blackening / baffles and masks / off state control

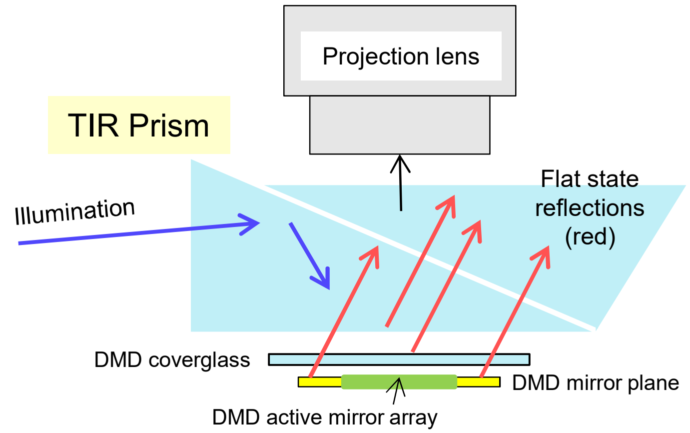
Example of OFF STATE projection pupil image filled with scattered light

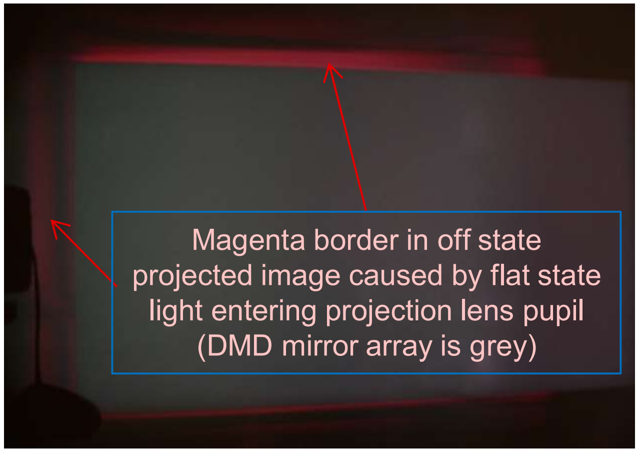
Flat state light entering projection lens pupil



Flat State Light

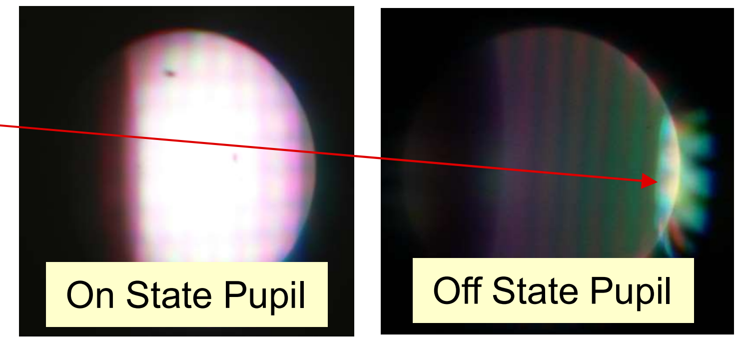
- Light from the illumination beam reflecting from any flat surface between the DMD and the projection lens
- Prism faces, the DMD coverglass or the flat surface outside of mirror array contribute to flat state light
- Reflections from the coverglass or prism faces that are directly above the mirror array cause lower contrast if allowed to pass through the projection lens
- Reflections from outside of the mirror array create a magenta border (if this is seen, there is flat state light entering the projection lens lowering system contrast)

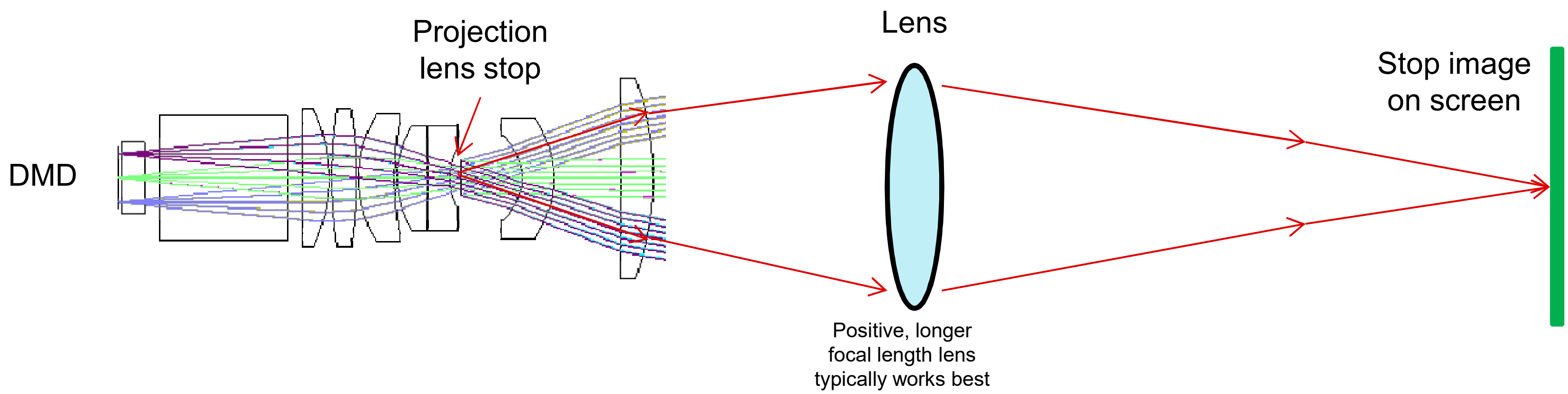




“The Magic Eye” Technique

- A simple method for examining the exit pupil of a projector
  1. Mount a lens in front of the projection lens
  2. Image the stop of the projection lens to a screen
- Shows where light is leaking through the pupil when mirrors are off
- To improve contrast, add system apertures to block unwanted light



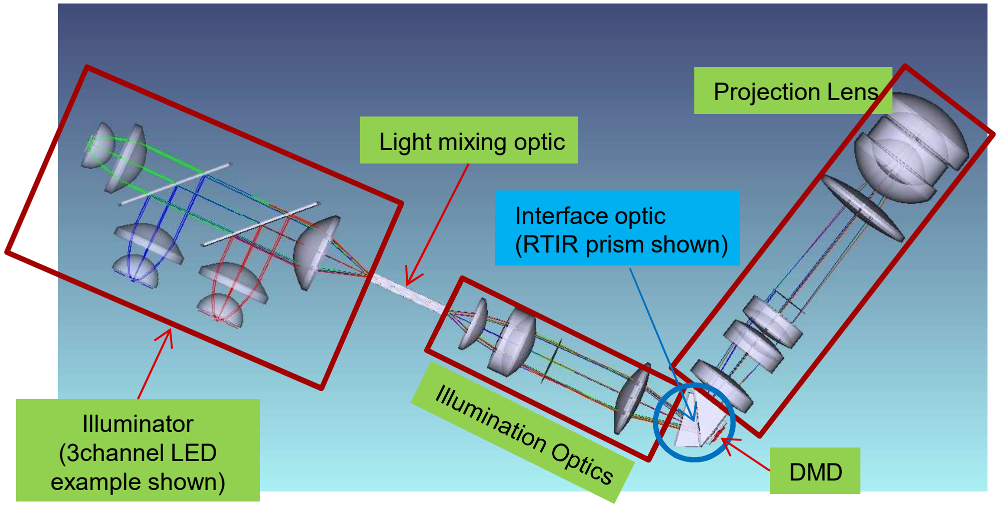


TEXAS INSTRUMENTS

Projection Architectures and Design

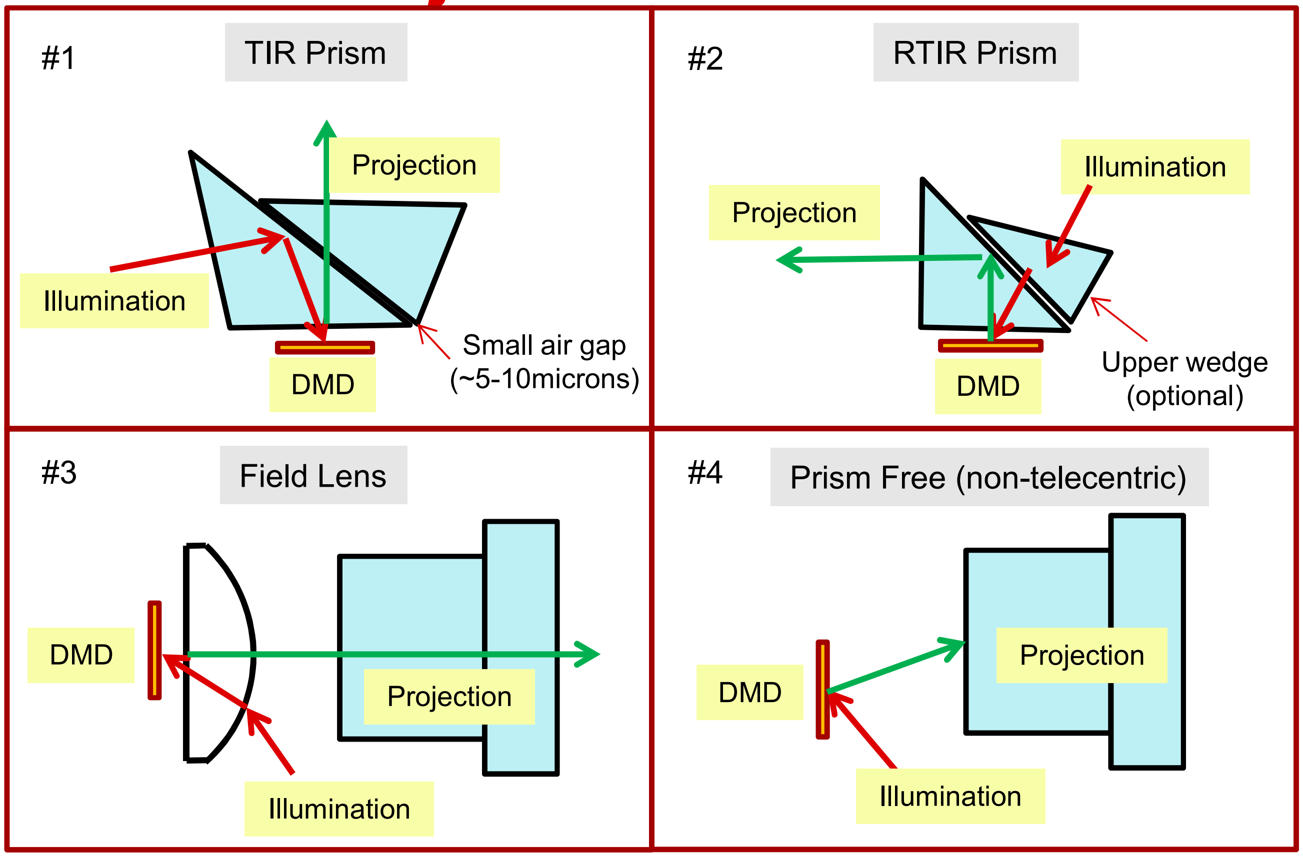
Projector System Layout & Design Options

- There are many options for designing a DLP projector
- Goal is to select the best configuration for the application:
  - **Illumination source** (and system F/#)
    - LED, laser phosphor, or direct RGB laser
  - **Illumination architecture** (main interface optic)
    - RTIR prism, TIR prism, Field lens, prism free (non-telecentric)
  - **Light mixing optic** (aka light integrator or homogenizer)
    - Tunnel or fly's eye array
  - **Projection lens**
    - Throw ratio, zoom, image offset (lens shift), MTF, etc.



Basic parts of a single chip DLP projector

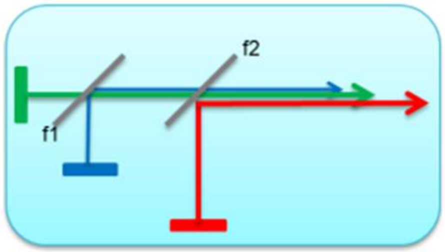
Four Basic DLP Projector Architectures



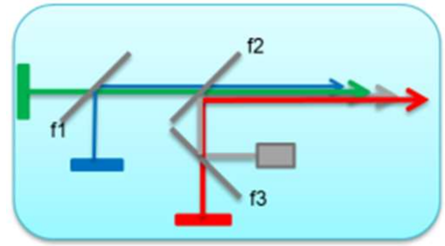
Light source Illuminator System Design

Illuminator: LED layout options

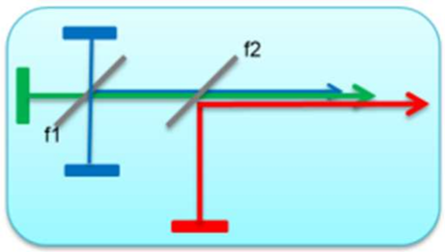
RGB
(3 channel)



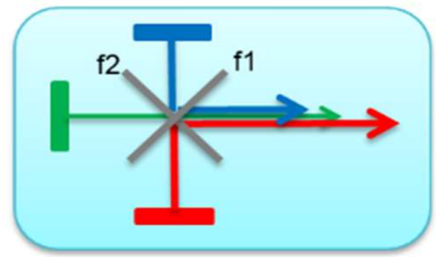
High Efficiency
(4 Channel)



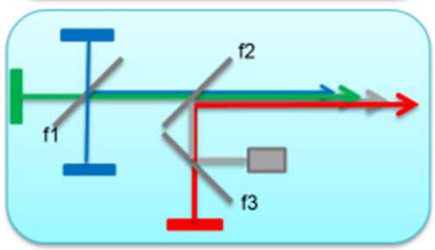
RGBB – Top Side Pump
(4 channel)



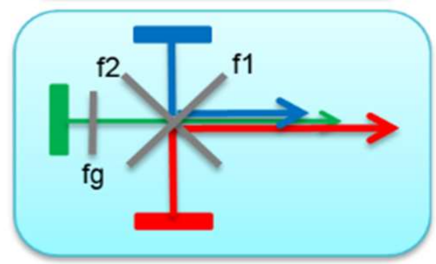
Compact
(3 Channel)



Long Wavelength Red
Assist
(5 channel)



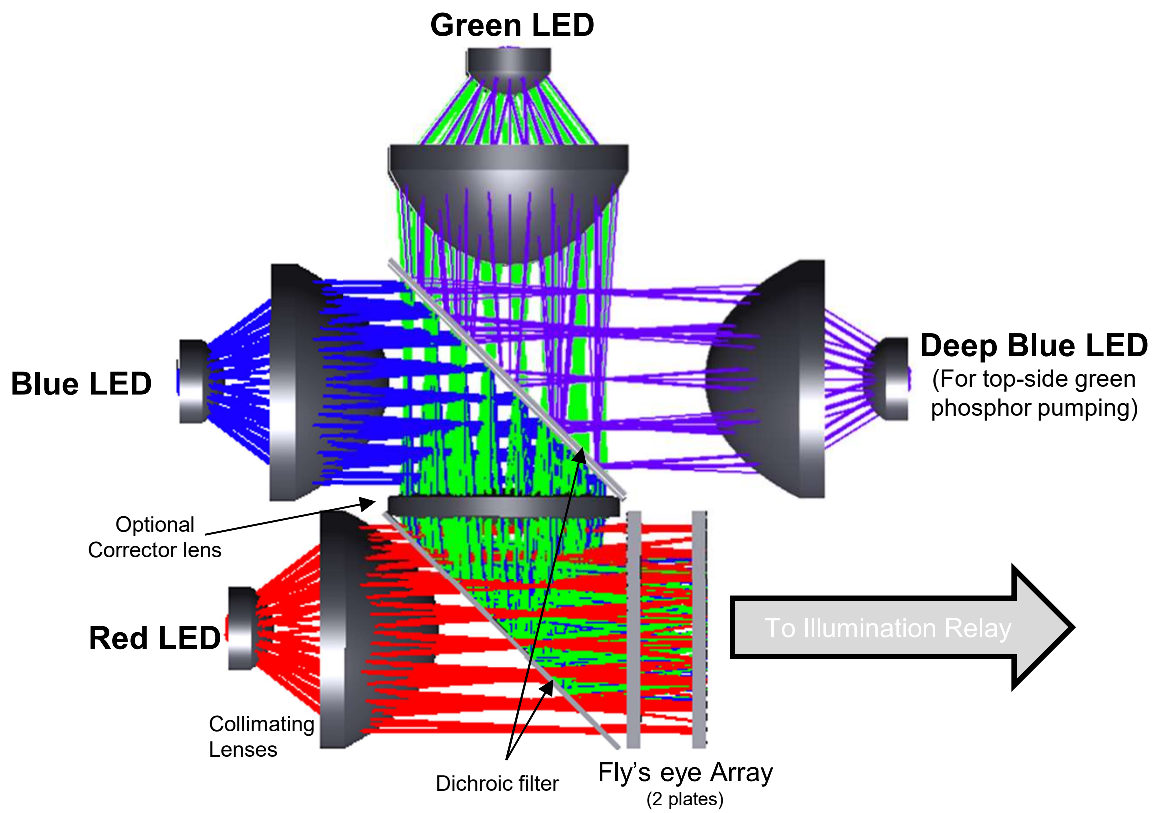
P3 (wide) Color Gamut
(3 Channel)



For more information on LEDs, refer to application brief " LED Guide for Mainstream Projectors" https://www.ti.com/lit/pdf/DLPA130

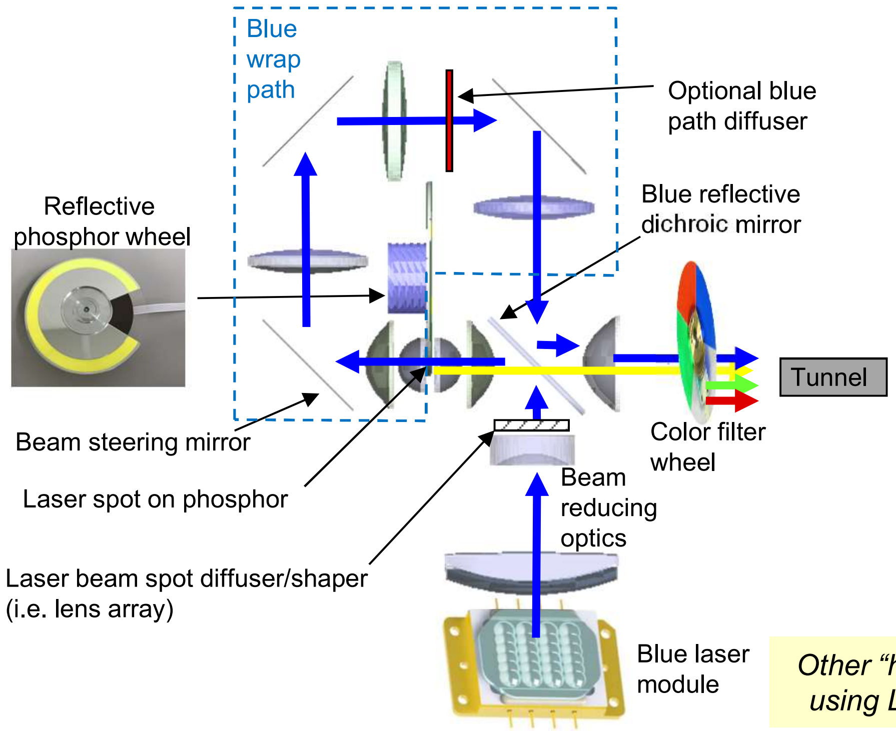
Illuminator: LED layout

4 channel using fly's eye example

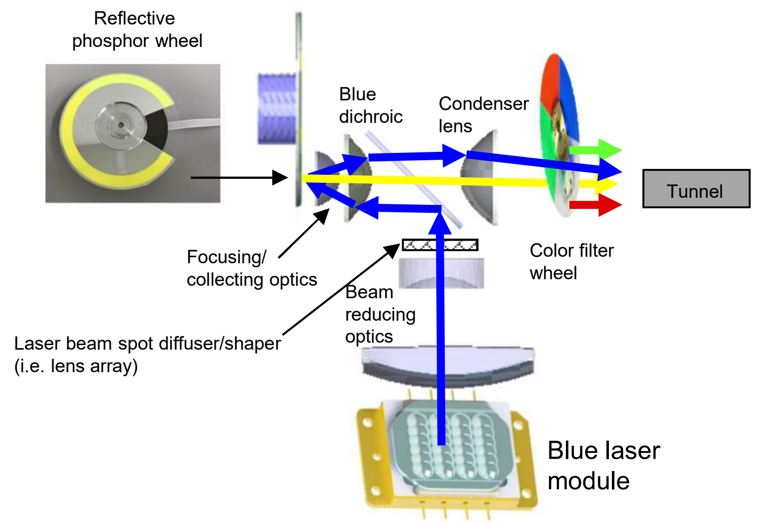


Illuminator: Laser Phosphor

Traditional layout



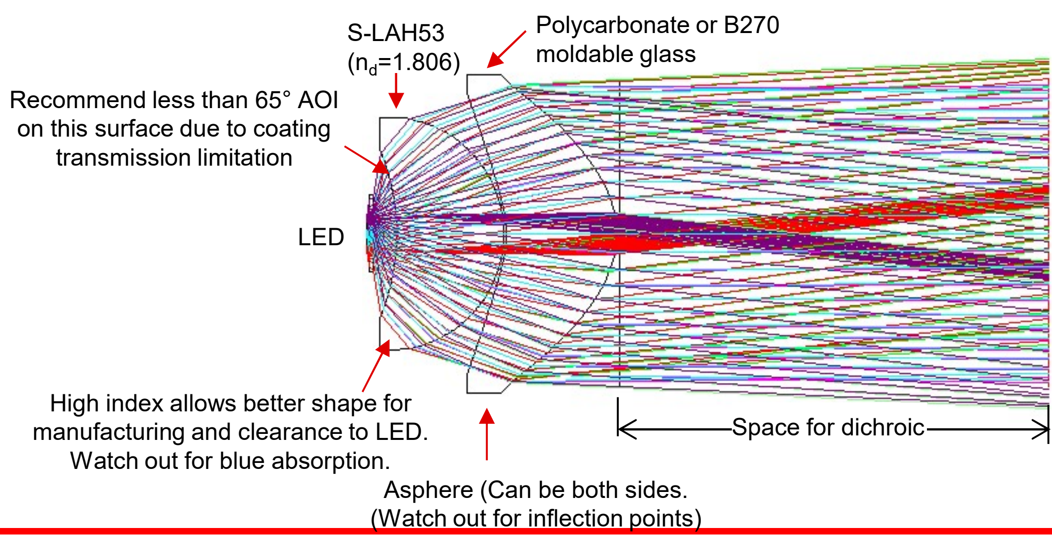
Compact layout
(eliminating blue wrap path)

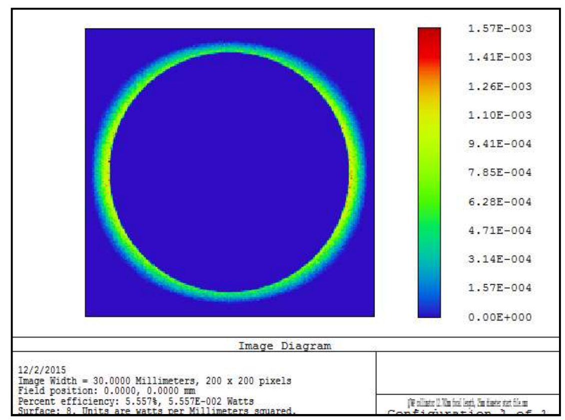


Other "hybrid" architectures where adding a separate green and/or red channel using LED or Laser are possible to improve color gamut or system efficiency.

Collimator design example for LED and LaPh

- Typically designed for ideal LED size, matched to DMD for maximum efficiency
  - Don't forget to include LED coverglass if included with LED. Efficiency is sensitive to LED collimator focus/alignment
- LED collection half angle of ±70° to ±80° out of Lambertian ±90°
  - Smaller collection angle results in easier design and manufacturability while trading off efficiency
- Optimize for a specific focal length or illumination pupil size ('angular radius' in Zemax)
  - Focal length and pupil size must be Etendue compatible with rest of the system (i.e. fly's eye array, relay optics, DMD) for maximum efficiency





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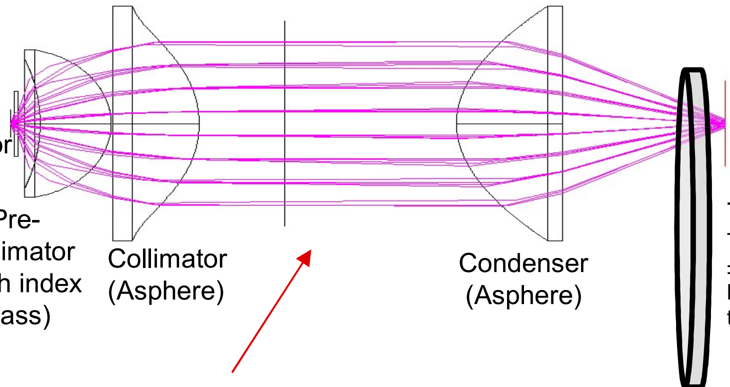
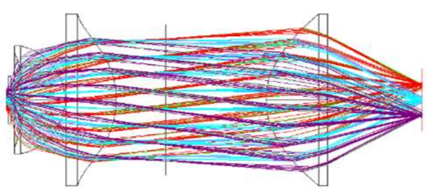
LED/Phosphor to Fly's Eye Array (FEA) / Tunnel

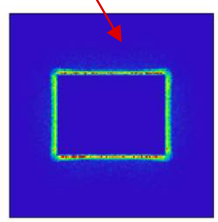
Tunnel-based



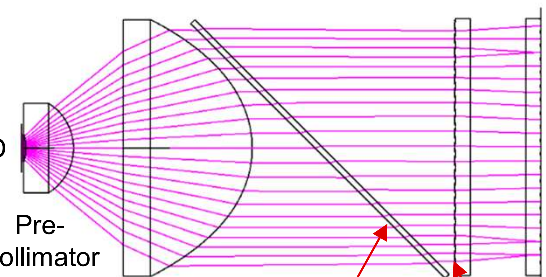
Collimated Space :
Diameter is dependent on Etendue which tell you size of dichroic needed (leave enough distance between lenses for filter)

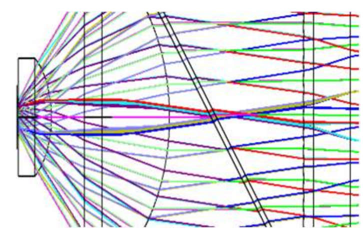


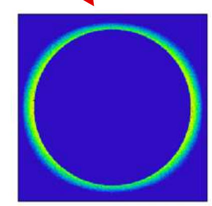
Color filter
wheel location
(LaPh
architecture)



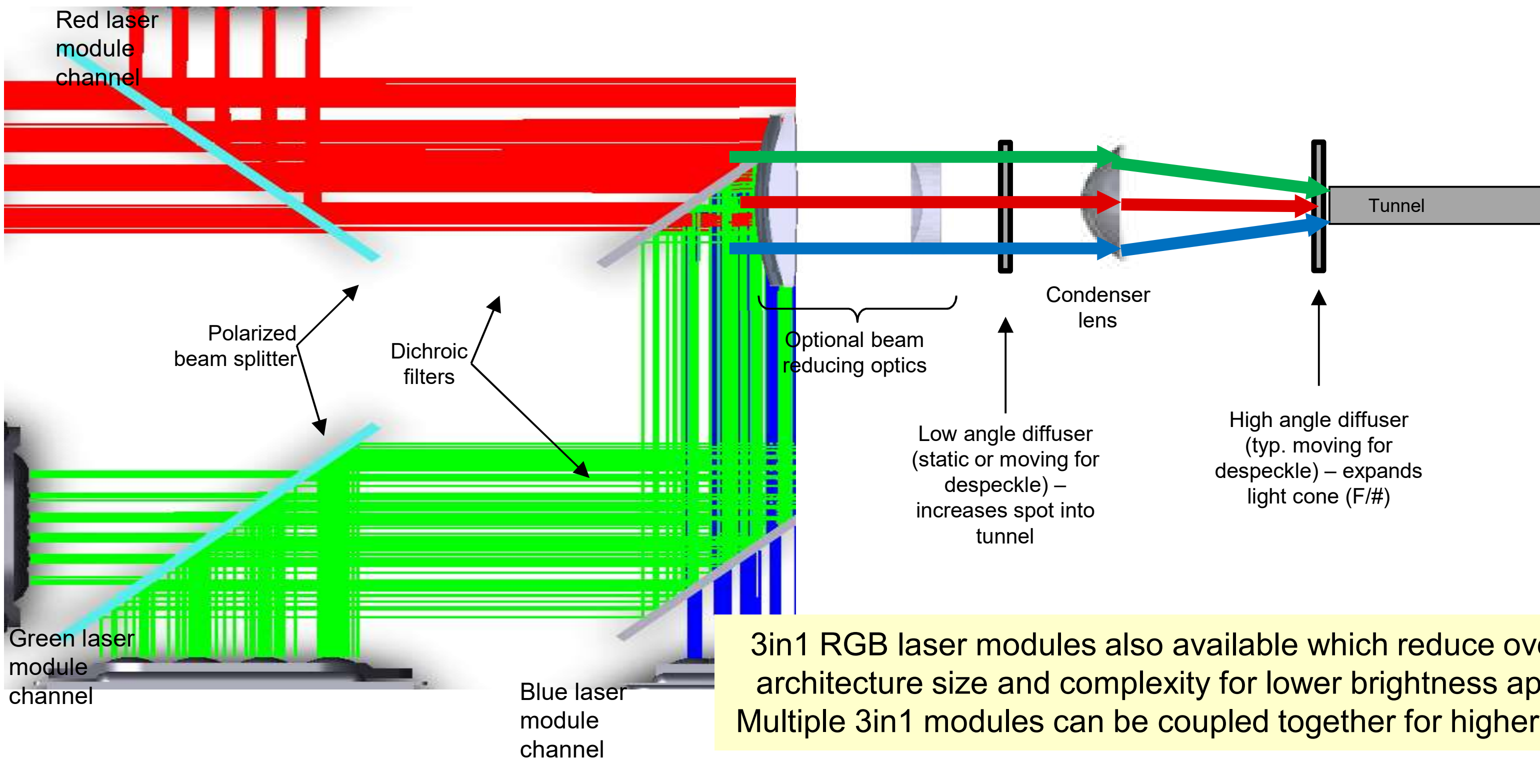
FEA-based







Illuminator: RGB Laser layout example

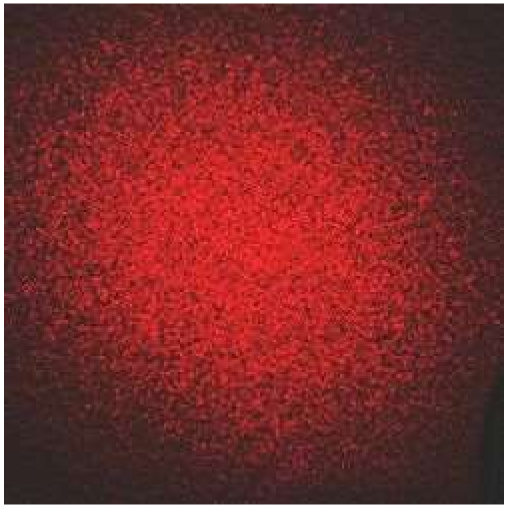


3in1 RGB laser modules also available which reduce overall optics architecture size and complexity for lower brightness applications. Multiple 3in1 modules can be coupled together for higher brightness.

Note: Red/Green channels show 2 modules split using polarization (rotated 90° to one another) – optional depending on brightness/power needed

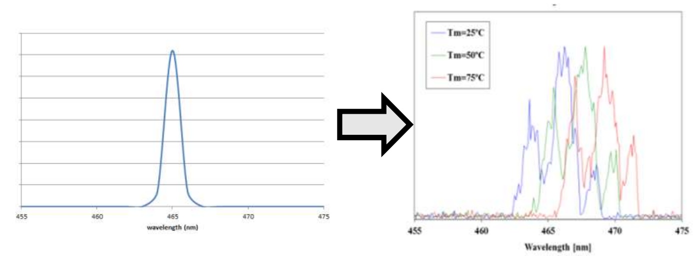
Laser Speckle

- High coherence of laser light causes speckle noise
  - Spatial coherence = small etendue
  - Temporal coherence = narrow spectrum
- Objective speckle = image intensity fluctuations (noise)
  - Relatively easy to mitigate with diffusers, etc.
- Subjective speckle- changes with head movement
  - Very difficult to mitigate
  - Limited by system (DMD) etendue
  - Longer wavelength → larger grain structure easier to see
  - High-gain screens exacerbate problem



Methods for Reducing Laser Speckle

- **Wavelength diversity**
  - Multiple diodes with slightly different wavelengths
  - Dual or triple wavelength red: 638nm + 642nm for example
  - Multiple diodes helps due to tolerances widening the wavelength bandwidth

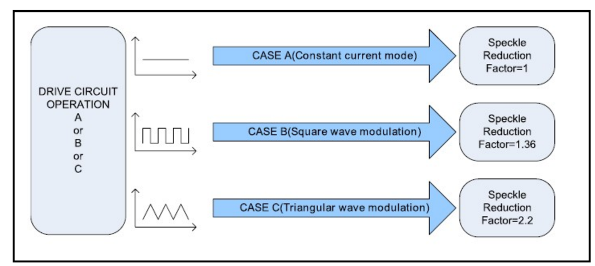


- **Spatial and angular beam diversity**
  - Beam shaping using static diffusers for better homogenization
  - Temporal diversity: moving diffusers to randomize phase

https://www.optotune.com/laser-speckle-reducers

- **Polarization diversity**
  - Multiple laser paths with rotated polarization – circular vs. linear polarization
  - Adding a waveplate for polarization scrambling

- **Laser current modulation** (square, triangular, sawtooth & other waveforms)
  - More impactful for single diode systems



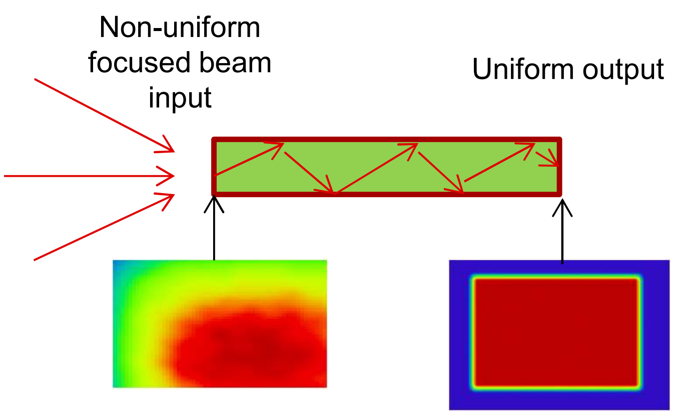
Yilmazlar, I., and M. Sabuncu. "Implementation of a current drive modulator for effective speckle suppression in a laser projection system." *IEEE Photonics Journal* 7.5 (2015): 1-6.

Illumination Relay Design

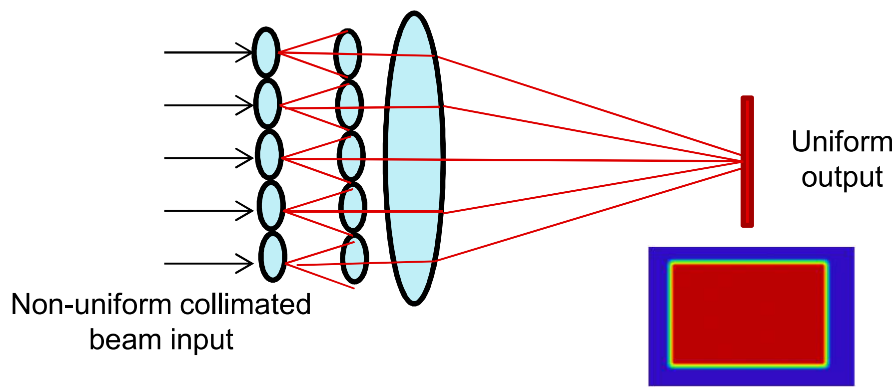
Light Mixing Options

- Illumination optics must illuminate the DMD uniformly for a uniform projected image
- Two methods commonly used to mix/homogenize light: Fly's eye array and Light tunnel

Light Tunnel



Fly's eye array



Light Mixing Options

- Examples:

Light tunnel

- Hollow light tunnels
- Highly reflective interior walls
- Tapered or straight
- Can be solid glass rods for high brightness

www.materion.com/products

Fly's eye array

- Glass or plastic
- Single double sided piece or two piece plates

http://www.isuzuglass.com/products/

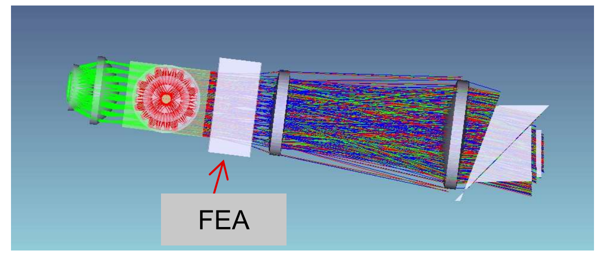
Light Tunnel vs. Fly's Eye Array Relay Optics

- Tunnel
  - Typically required for systems that use a color wheel (i.e. lamp, laser phosphor) or lasers with specific despeckling requirements
  - Much larger in overall length than FEA design
  - Lowest stray light and easiest for design and alignment
  - Recommend hollow tunnel to avoid dust, scratches on ends of tunnel. Solid fused silica rods may be necessary for very high lumen projection systems.
  - Disadvantage: Longer illumination optics

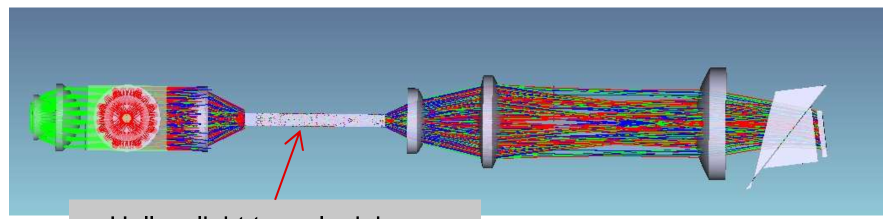
- Fly's Eye Array
  - Most common with LED-based illuminators but can be used with laser systems also (no color wheel)
  - More compact with less elements
  - Generally does not require aspheric optics

- System apertures recommended for stray light from FEA cell crosstalk or light tunneling at edges of tunnel (see next slide)

Note: designs shown are for comparison only



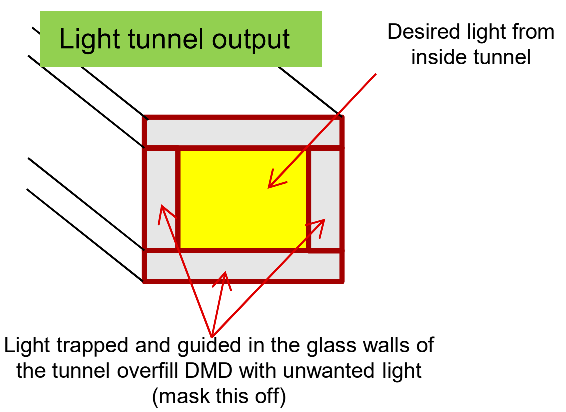
FEA

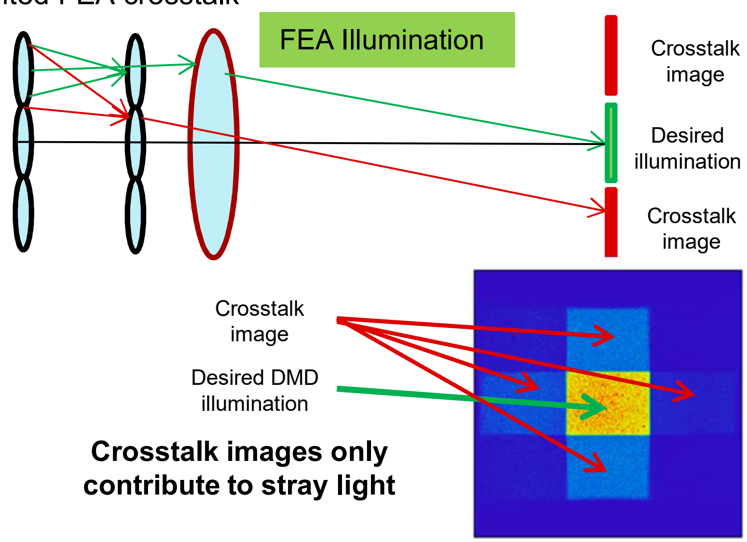


Tunnel

Crosstalk and Tunneling in FEA and Tunnel

- Hollow light tunnel may have light tunneling in walls
- Lens array crosstalk will lead to multiple illuminated areas on DMD
- Mitigation options:
  - Aperture or blacken tunnel wall faces (paint on output / metal mask on input)
  - Design FEA for minimal crosstalk
  - Paint aperture on DMD side of prism to mask off unwanted FEA crosstalk
  - Mechanical baffles

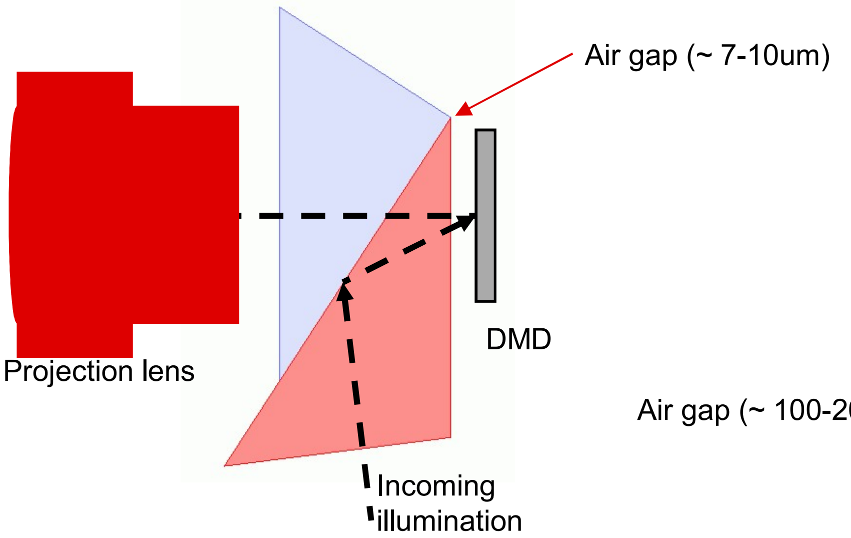




TIR and RTIR Prism architectures

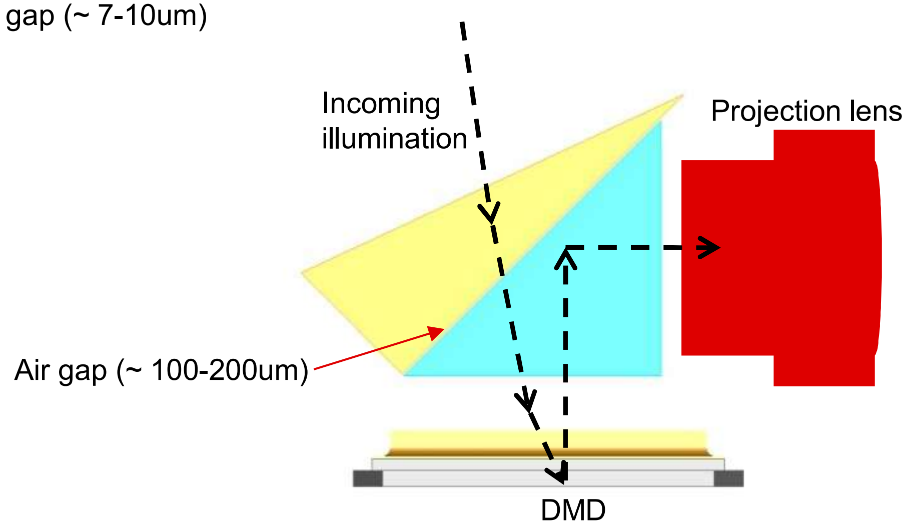
Used to separate illumination and projection light bundles

Traditional TIR



- Project through air gap
- Tightly control air gap to reduce aberrations (typically <0.01mm)

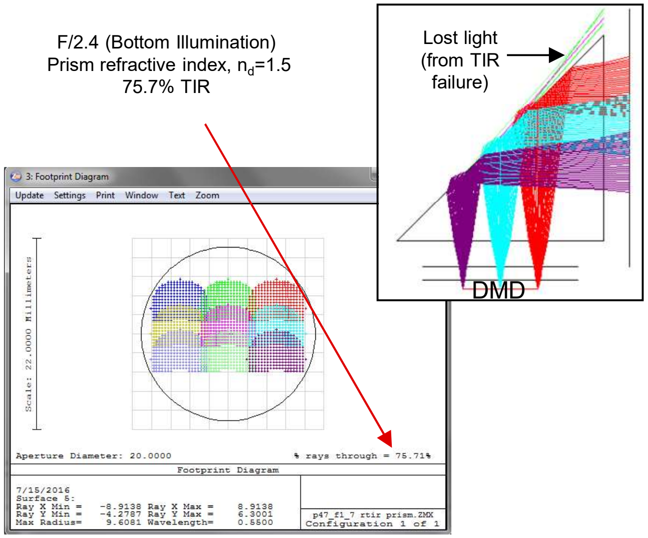
Reverse TIR

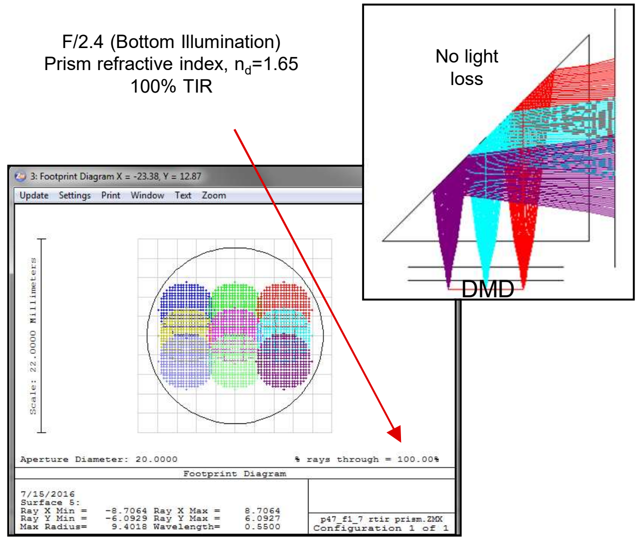


- Illuminate through air gap
- Air gap not as critical (typically <0.2mm)

Prism Material Selection

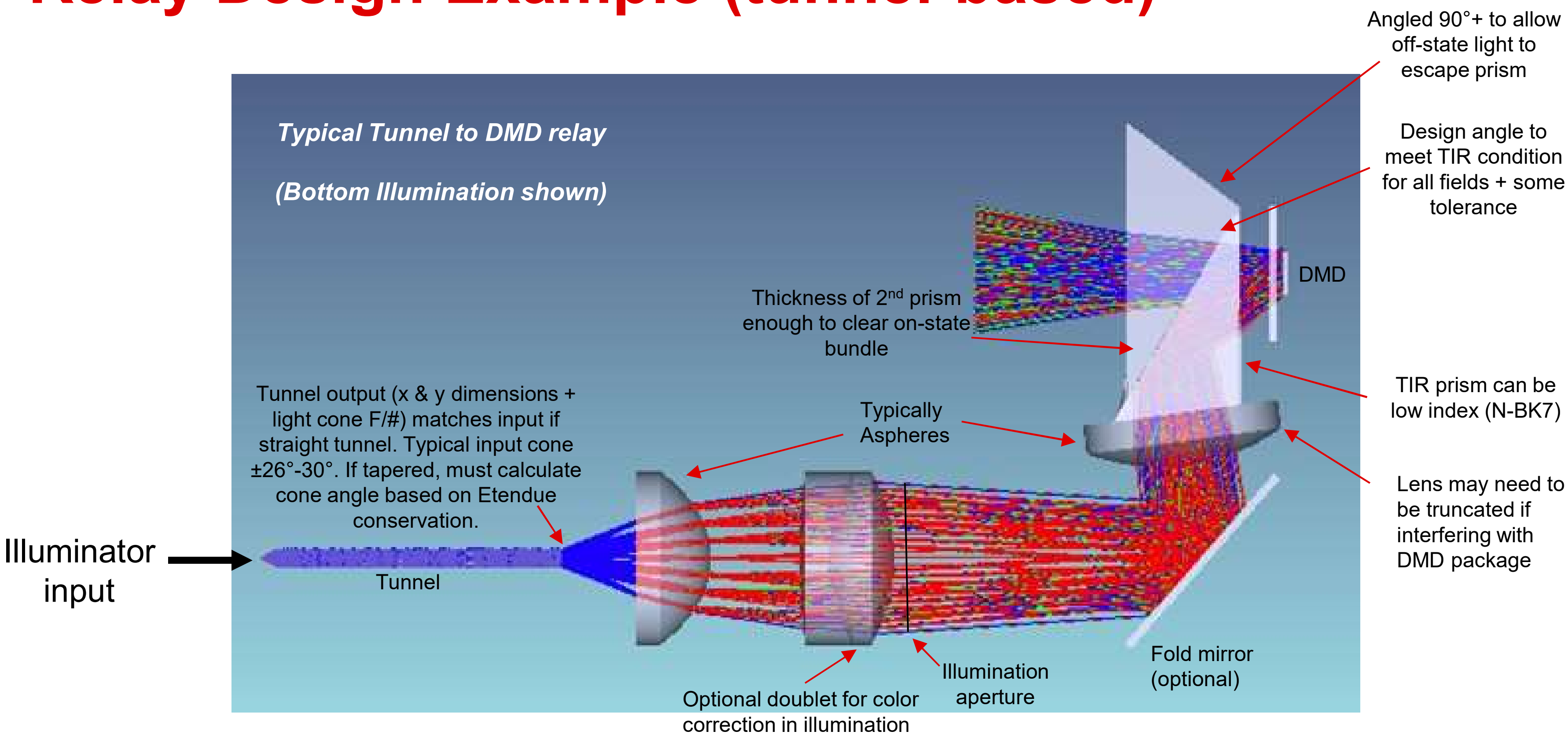
- Critical for RTIR only. TIR prism are typically N-BK7 or equivalent for cost
- Depending on F/# of system, prism material index must be selected to meet TIR condition at all fields at 45° prism interface



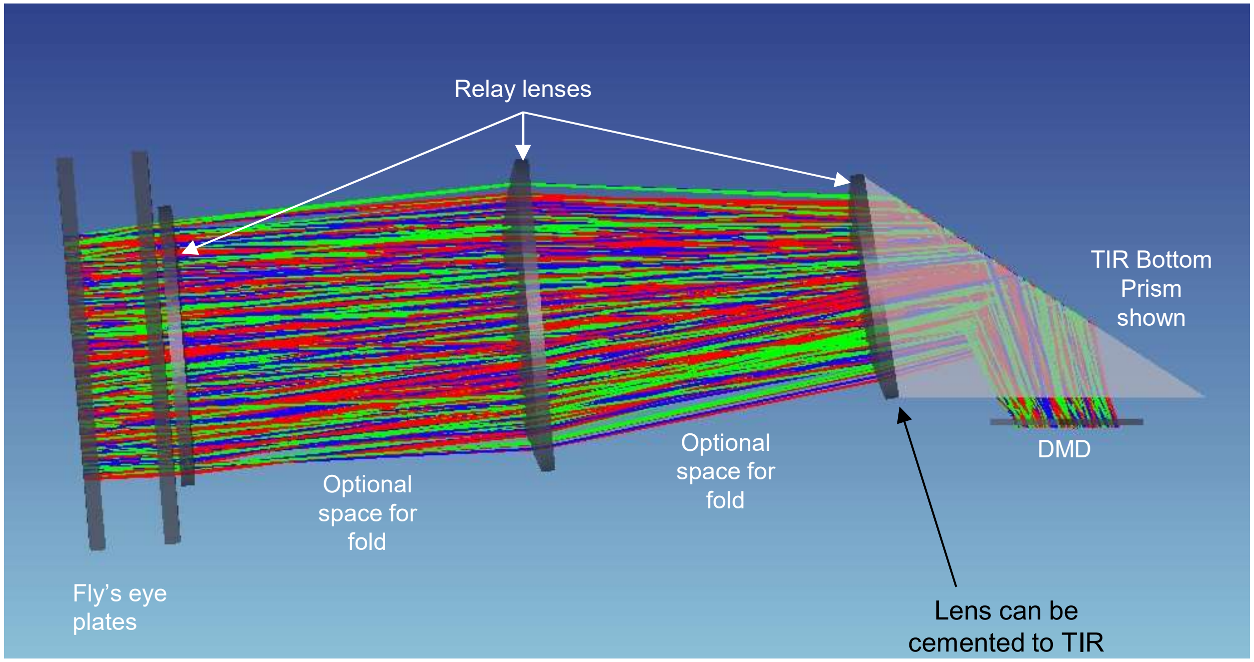


Prism glass material	nd	Symmetric Half Angle	F/#	% Flux to PJ lens		
				0° offset	1° offset	2° offset
BK7	1.517	12	2.40	0.8085	0.8513	0.8917
		13	2.22	0.7909	0.8312	0.8683
		14	2.07	0.7754	0.811	0.8484
		15	1.93	0.7609	0.7954	0.831
		16	1.81	0.7475	0.783	0.8147
		17	1.71	0.736	0.7719	0.8001
BAK4	1.569	12	2.40	0.9224	0.953	0.98
		13	2.22	0.8984	0.9319	0.9588
		14	2.07	0.8779	0.911	0.9389
		15	1.93	0.858	0.8903	0.9198
		16	1.81	0.8411	0.8717	0.8997
		17	1.71	0.8259	0.8555	0.883
N-SK5	1.589	12	2.40	0.9553	0.9819	0.9981
		13	2.22	0.9343	0.9607	0.9839
		14	2.07	0.9126	0.9405	0.9647
		15	1.93	0.8922	0.9221	0.9465
		16	1.81	0.8741	0.9028	0.929
		17	1.71	0.8574	0.8853	0.9127
N-SK4	1.613	12	2.40	0.9867	0.9997	1
		13	2.22	0.967	0.9886	0.9998
		14	2.07	0.9469	0.9713	0.9898
		15	1.93	0.928	0.9525	0.9753
		16	1.81	0.9108	0.9361	0.9574
		17	1.71	0.8926	0.9192	0.9409
N-LAK22	1.651	12	2.40	1	1	1
		13	2.22	0.9999	1	1
		14	2.07	0.9902	0.9999	1
		15	1.93	0.976	0.991	0.9999
		16	1.81	0.9582	0.9782	0.9921
		17	1.71	0.9416	0.9614	0.9799
N-BAF10	1.67	12	2.40	1	1	1
		13	2.22	1	1	1
		14	2.07	1	1	1
		15	1.93	0.991	1	1
		16	1.81	0.9782	0.9922	1
		17	1.71	0.9617	0.9801	0.9936
N-LAK9	1.691	12	2.40	1	1	1
		13	2.22	1	1	1
		14	2.07	1	1	1
		15	1.93	1	1	1
		16	1.81	0.9937	1	1
		17	1.71	0.9816	0.995	1

Relay Design Example (tunnel-based)



Relay Design Example (Fly's eye array - based)



- 2-3 lens typical
- Aspheres optional
- Fly's eye array (FEA) can be either 2 independent pieces or a single molded part

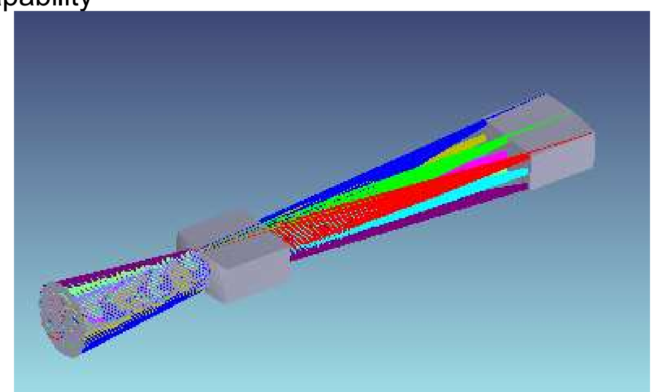
Fly’s Eye Array Design Method / Tips

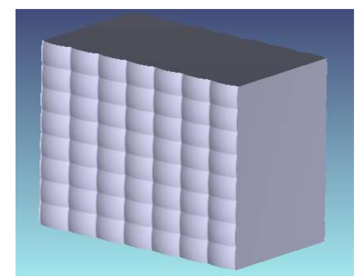
- FEA can be separate plates or 1 monolithic molded element
- Glass recommended in high brightness applications due to flux density. Polycarbonate may be okay at lower lumen levels.
- Illumination pupil size determined by system Etendue and collimator design (focal length)
- Pupil Sampling: 10-12 lens array cells minimum along long dimension for good homogenization and DMD uniformity
- Once cell size is determined, focal length can be calculated based on LED to FEA or FEA to DMD magnification
  - Design FEA based on focal length
  - Edge Thickness or form depends on manufacturing capability

Lens Data Editor

Edit Solves View Help

Surf	Type	Comment	Radius		Thickness		Glass
OBJ	Standard		Infinity		Infinity		
1	Standard		Infinity		5.0000000		
*	Standard		6.5200000		2.5000000		B270
3*	Standard		Infinity		8.9300000		
4*	Standard		Infinity		2.5000000	P	B270
5*	Standard		-6.5200000	P	0.0000000		
IMA	Standard		Infinity		-		





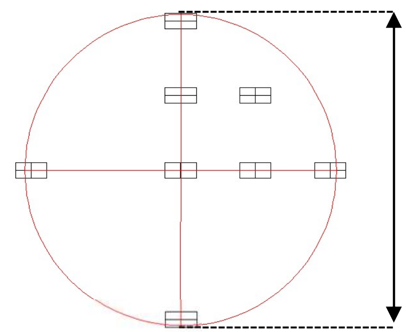
FEA-based Relay Design Method / Tips

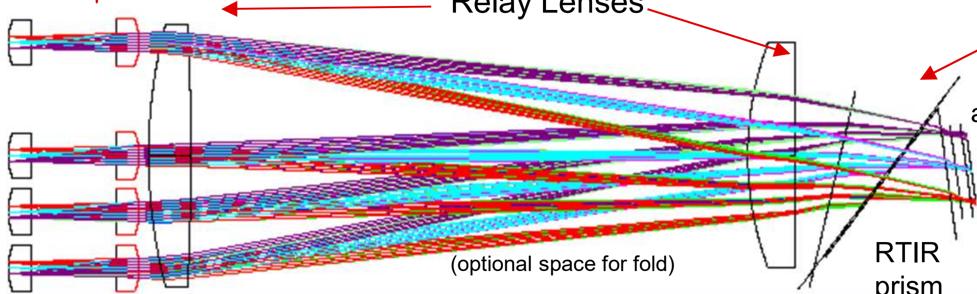
- Easiest design method uses a multi-configuration of several lens array cells sampling the illumination pupil
  - Shift in X and Y after the FEA and design relay system
- Field Size set to lens array cell dimension, “Aperture” set to pupil diameter of each cell (y-height)
- 2 Lens relay typical
  - Aspheres not necessary but do help with some aberration control

Multi-Configuration Editor

Edit Solves Tools View Help

Active : 1/8		Config 1*	Config 2	Config 3	Config 4	Config 5	Config 6	Config 7	Config 8
1: MOFF	0								
2: PRAM	6/1	0.0000000	0.0000000	0.0000000	-6.0000000	12.0000000	-6.0000000	-12.0000000	0.0000000
3: PRAM	6/2	0.0000000	6.0000000	12.0000000	0.0000000	0.0000000	6.0000000	0.0000000	-12.0000000
4: MOFF	0								

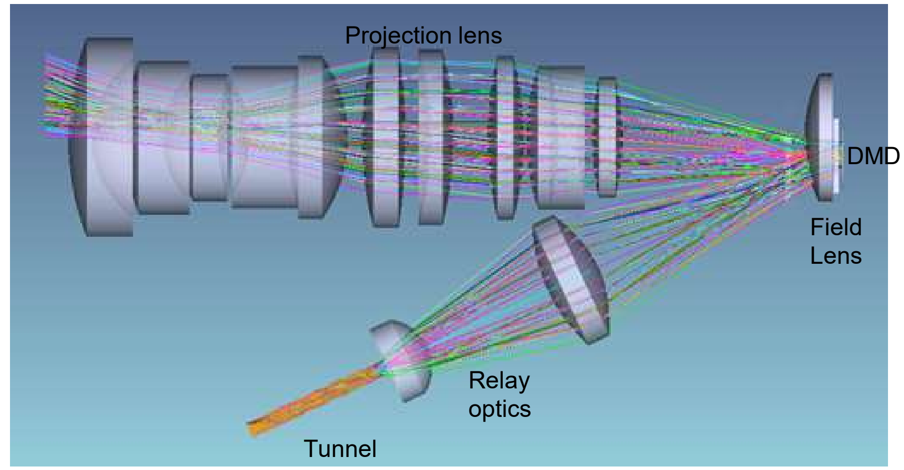




Texas Instruments

Field Lens Architecture

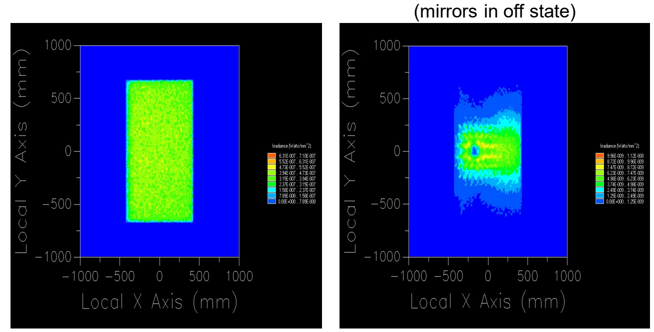
- Can be used with light tunnel or FEA
- Field lens is shared between illumination and projection lens, placed directly in front of DMD
- Field lens separates illumination and projection light bundles without the need of a prism
- Projection lens tends to be smaller
- Telecentricity can be maintained



- NOTE: Specular reflections from illumination light incident on field lens surfaces may create a stray light reflection on the screen resulting in lower contrast
  - Highly dependent on shape (curvature) of field lens
  - If considering a field lens architecture, evaluate stray light reflections created from illumination light incident on field lens surfaces

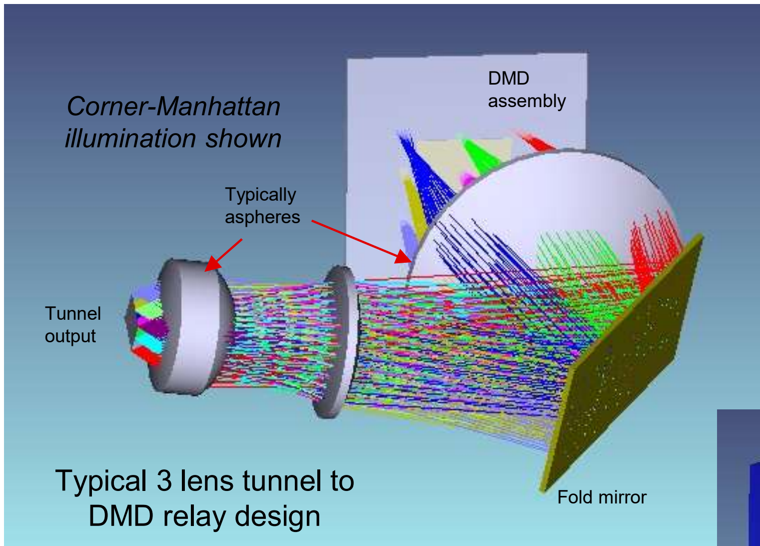
On State Light

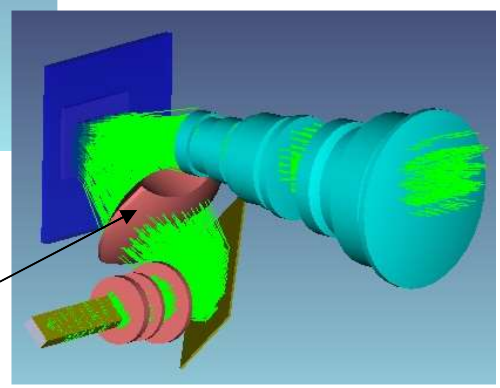
Field Lens Ghosting
(mirrors in off state)



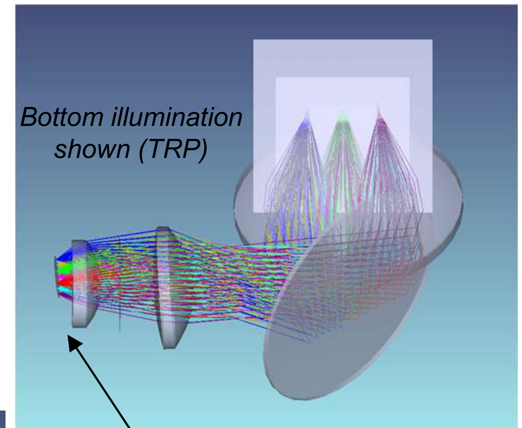
Relative Power:	100%	0.52%

Non-telecentric illumination considerations





Last illumination lens typically cut to give space for projection lens (this will incur some efficiency loss)

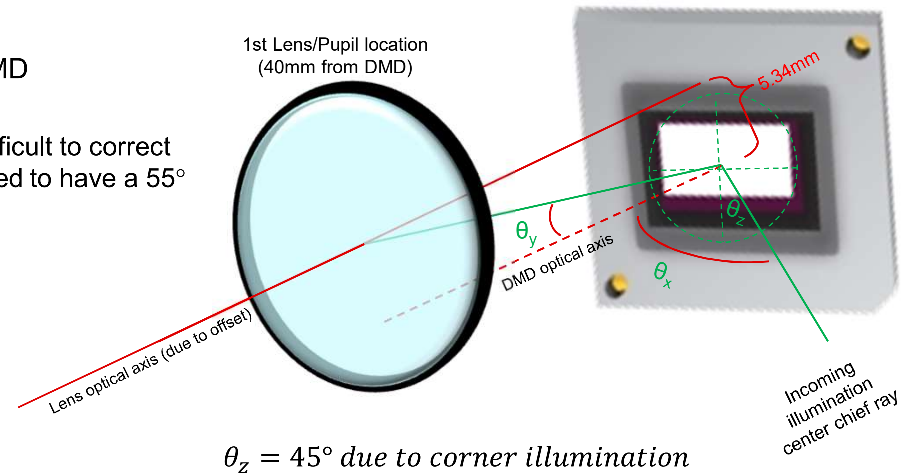


Schiempflug (tilt) can be added to improve distortion and/or anamorphism of tunnel to DMD relay

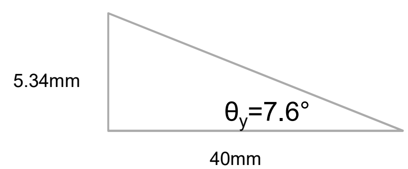
Non-telecentric pupil matching

- Non-telecentric systems require illumination exit pupil to match projection entrance pupil (from DMD side) in size and position for maximum system efficiency
- For 0.65” 1080p, projection lens pupil is typically 30-40mm from DMD
  - Further pupils, chief ray angles become closer to telecentric
  - Closer pupils, chief ray angles become steep on DMD → more difficult to correct anamorphism, distortion without using a prism (DMD recommended to have a 55° max ray angle)
- Offset must be considered for non-telecentric
  - Needed to separate illumination and on-state light bundles
  - A minimum of 100% image offset is typically required
- Calculation on right assumes the following:
  - 0.65” 1080p s450 (14.592mm x 8.208mm)
  - Corner illumination – 45° rotation w.r.t. DMD array
  - 12° mirror tilt
  - 130% vertical image offset only
  - 40mm pupil location

Sample calculation:



$\theta_z = 45°$ *due to corner illumination*



$$\textbf{Illumination angle} = 2 \times \textbf{mirror tilt} + \theta_y = 2 \times 12° + 7.6° = 31.6°$$

Non-telecentric Relay Design Method / Tips

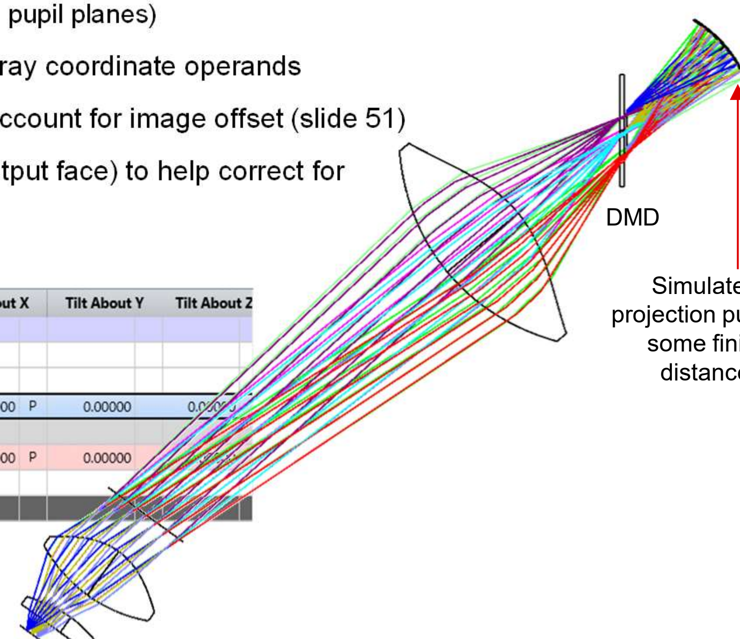
- Constrain pupil position to match projection pupil
  - Can use EXPP operand in Zemax (more accurate for paraxial system not real systems)
  - Set individual real ray coordinate operands to zero (chief rays are at 0,0 at pupil planes)
- Constrain F/# using WFNO or through calculated pupil diameter using real ray coordinate operands
- Constrain incident angle onto DMD based on 2x pixel tilt + offset angle to account for image offset (slide 51)
- Illumination lenses can be off-axis (tilted or decentered relative to tunnel output face) to help correct for distortion / tilted focus plane – "Scheimpflug"

	Surface Type	Comment	Radius	Thickness	Material	Decenter X	Decenter Y	Tilt About X	Tilt About Y	Tilt About Z
18	Standard	DMD Window	Infinity	1.10000	EAGLE...					
19	Standard		Infinity	0.70300						
20	Standard	DMD plane	Infinity	0.00000						
21	Coordinate Break	Distance to Pupil		35.00000	-	0.00000	0.00000	40.70000 P	0.00000	0.0[illegible]
22	Standard	Pupil - retroreflect back to DMD	-35.00000	-35.00000	MIRROR					
23	Coordinate Break	Back to DMD		0.00000	-	0.00000	0.00000	-40.70000 P	0.00000	
24	(aper) Standard	DMD Plane	Infinity	0.00000						
25	(aper) Standard	DMD aper/obsc	Infinity	0.00000						

Pupil distance

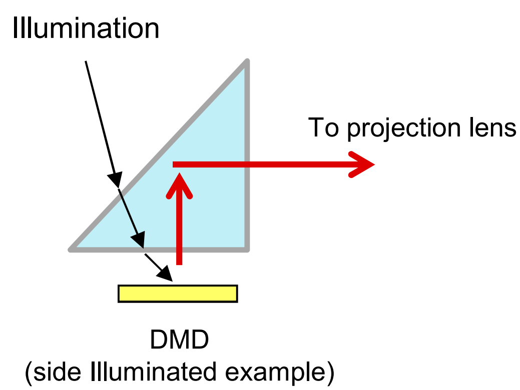
Retroreflect back to DMD to allow for spatial and angular optimization at the same time

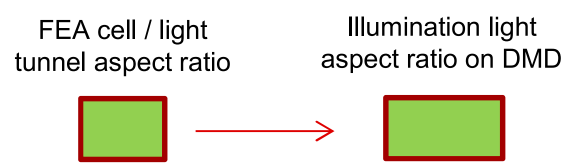
Accounts for DMD illumination angle



Anamorphism in Illumination Optics

- Anamorphism (unequal magnification in x and y) between the light mixing optic and DMD needs to be taken into account in the design
- Anamorphism is caused by path of light in prisms (TIR and RTIR) and the oblique illumination angle of incidence
- Typical numbers range from ~ 1.05 to 1.3 depending on system
  - TIR prism has very low anamorphism (~1 to 1.1x typical)
  - RTIR with upper wedge has low anamorphism (~1 to 1.1x typical)
  - RTIR (right angle prism) has largest anamorphism (~ 1.3x typical)
- Anamorphism results in loss of etendue (LED usable area is smaller)



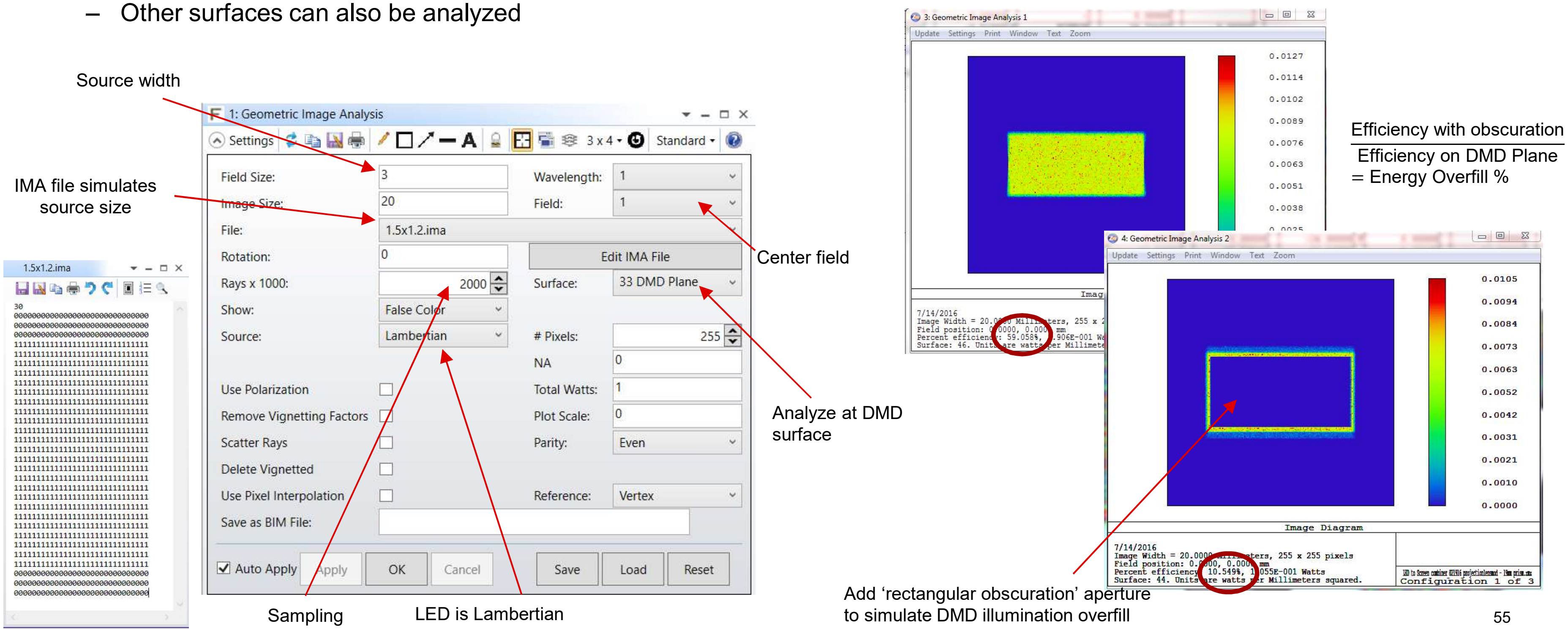


~ 1.3 X stretching from illumination to DMD surface

* Note: If bottom illuminated, stretching is in the vertical direction

Zemax Modeling Tip : Irradiance Analysis

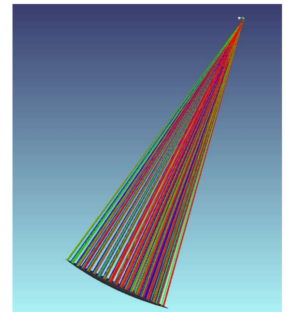
- To model the illumination profile including overfill on DMD, use “Geometric Image Analysis”.
  - Other surfaces can also be analyzed

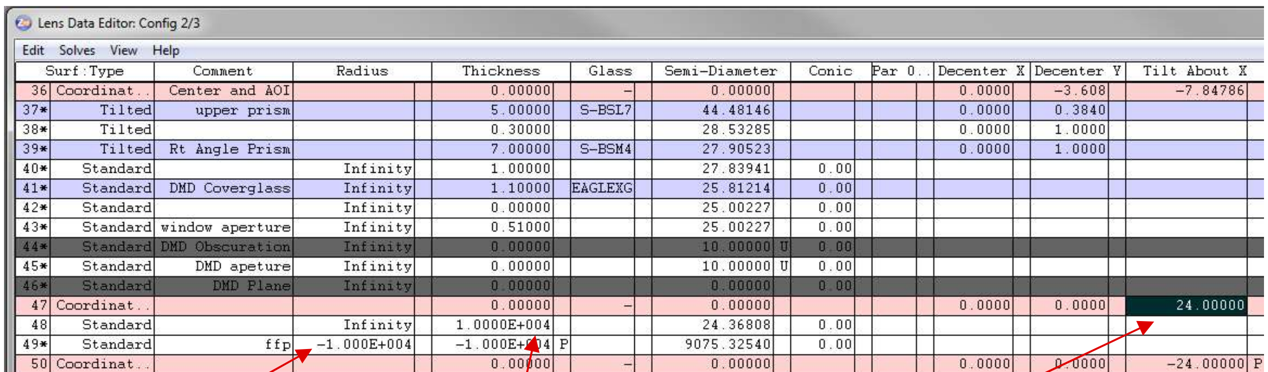


Texas Instruments

Zemax Modeling Tip: Far Field Analysis

- Used to analyze F/# and pupil in telecentric systems



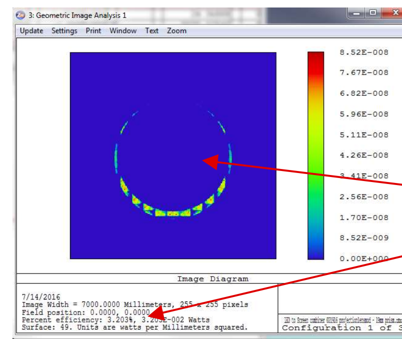


Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0..	Decenter X	Decenter Y	Tilt About X
36	Coordinat..	Center and AOI		0.00000	–	0.00000			0.0000	-3.608	-7.84786
37*	Tilted	upper prism		5.00000	S-BSL7	44.48146			0.0000	0.3840	
38*	Tilted			0.30000		28.53285			0.0000	1.0000	
39*	Tilted	Rt Angle Prism		7.00000	S-BSM4	27.90523			0.0000	1.0000	
40*	Standard		Infinity	1.00000		27.83941	0.00				
41*	Standard	DMD Coverglass	Infinity	1.10000	EAGLEXG	25.81214	0.00				
42*	Standard		Infinity	0.00000		25.00227	0.00				
43*	Standard	window aperture	Infinity	0.51000		25.00227	0.00				
44*	Standard	DMD Obscuration	Infinity	0.00000		10.00000 U	0.00				
45*	Standard	DMD apeture	Infinity	0.00000		10.00000 U	0.00				
46*	Standard	DMD Plane	Infinity	0.00000		0.00000	0.00				
47	Coordinat..			0.00000	–	0.00000			0.0000	0.0000	24.00000
48	Standard		Infinity	1.0000E+004		24.36808	0.00				
49*	Standard	ffp	-1.000E+004	-1.000E+004 P		9075.32540	0.00				
50	Coordinat..			0.00000	–	0.00000			0.0000	0.0000	-24.00000 P

Add radius for solid angle (depending on distance set)

Set far-field distance

Illumination AOI (if analyzing DMD far-field)



Circular obscuration to match F/# to determine how much light is lost

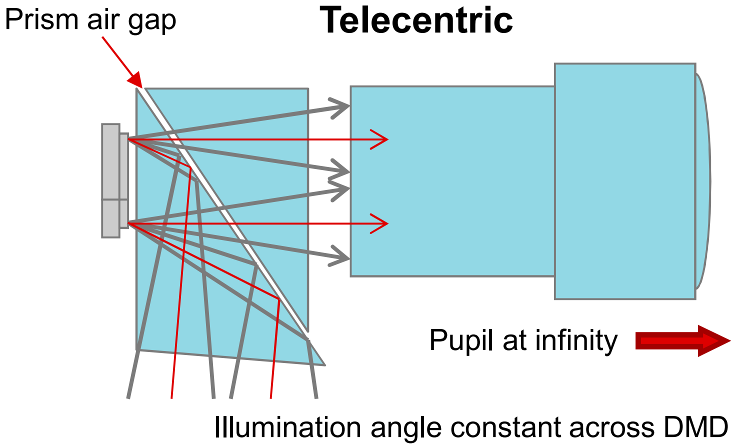
*Note: Circular obscuration radius= distance*sin(θ) where θ =half-angle*

Projection Lens Considerations

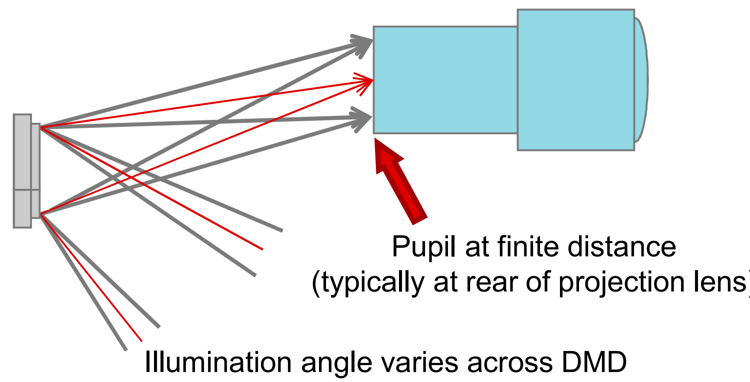
For additional information, visit: https://training.ti.com/common-projection-lens-specifications

Telecentric vs. Non-telecentric

Telecentric



Non-telecentric

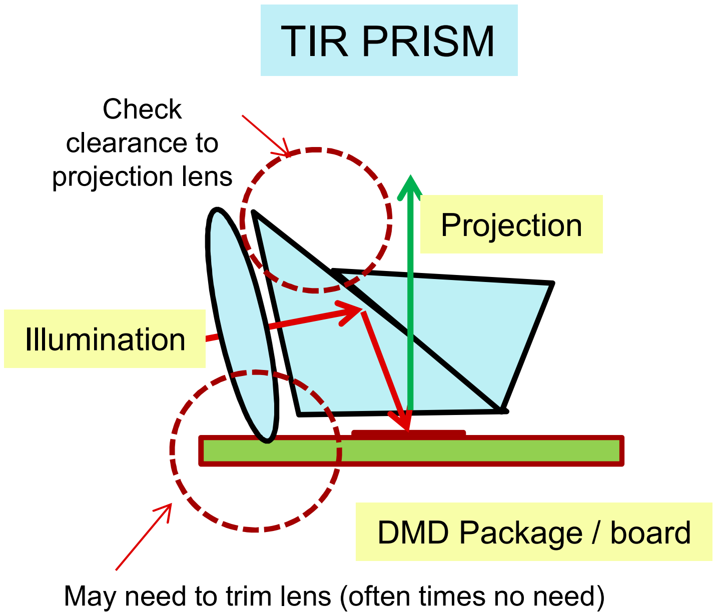


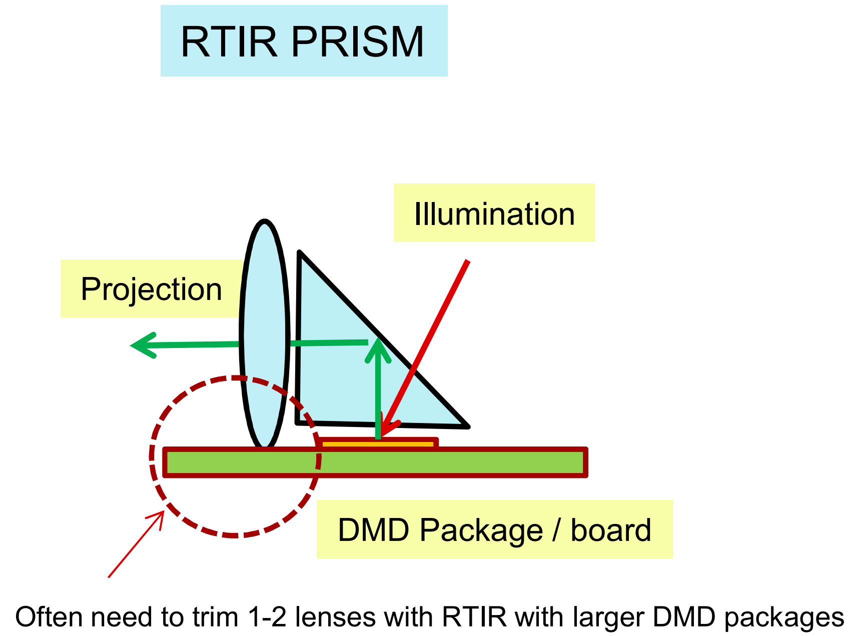
- Prism required to separate illumination and projection light paths
  - Air gap functions as angular filter via total internal reflection (TIR)
- Allows for interchangeable lenses
- Lens shift possible in design
- Image illumination uniformity is typically good
- Lens can be big especially with low F/#

- Lens offset required to separate illumination and projection light
- Lens must be pupil size and location matched to the illumination for maximum efficiency
  - More difficult to interchange lenses
- Lens shift not possible without sacrificing efficiency/brightness
- Image uniformity not as good as telecentric designs
- Lens is typically smaller and lower-cost

Trimming lenses in Prism Architectures

- TIR and RTIR may need lenses trimmed to avoid mechanical interference with DMD package or electronics
- May need to increase back working distance to minimize interference of DMD with projection lens and/or XPR actuator
- Always check mechanical clearances in design and move or adjust optics accordingly





Typical Projection Lens Design Targets

- Field Size: At minimum the field is the DMD size + image offset / lens shift (if any)
- F/#: Matched to the Illumination (for contrast optimization) or higher if aperture is adjustable
- MTF:
  - As designed: Polychromatic (All wavelengths): ≥50% at Nyquist Frequency $\left(\frac{1}{2*pixel\ size}\right)$
  - Nyquist Frequencies:
    - 10.8µm pixel: 46 line pairs/mm
    - 9.0µm pixel: 56 line pairs/mm
    - 7.6µm pixel: 66 line pairs/mm
    - 5.4µm pixel: 93 line pairs/mm
- Distortion: ≤1% (goal) <1.5% (acceptable). Other applications may allow more relaxed distortion.
  - TV Distortion: ≤1%
- Lateral Color: Between any two wavelengths target of ≤ ±0.5pixel and max of 0.75pixel at corners of field
- Telecentric vs. Non-Telecentric
  - Telecentric: Chief rays variation ≤0.5° preferred, ≤1.0° acceptable – this creates larger pupil and may introduce flat state light
  - Non-Telecentric: pupil position must be matched to illumination otherwise system may experience contrast issues or light loss
- Back focal/working distance: Must account for prism thickness and material (if applicable) as well as DMD window
  - Add XPR glass plate if applicable

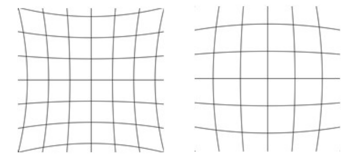


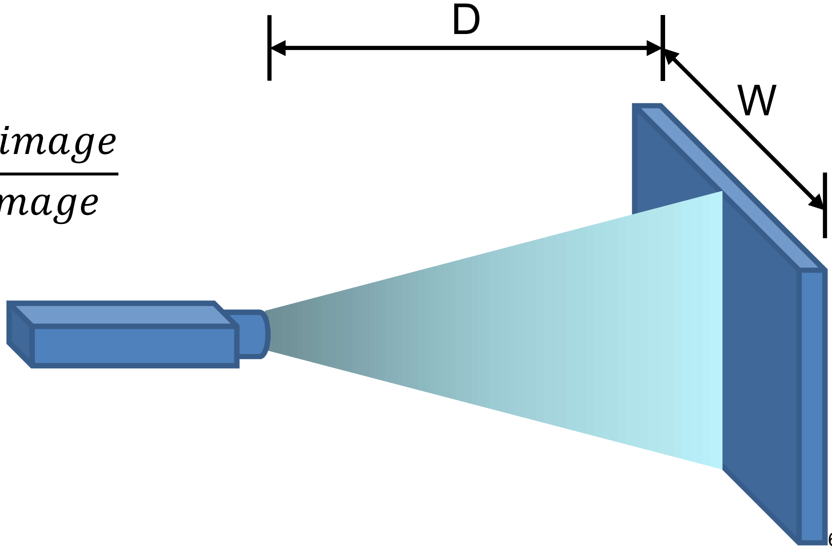
Image distortion

Lateral color

Throw ratio

- Throw ratio quantifies the size of an image created when a projector is placed a given distance from the screen.
- Small throw ratio systems can be placed closer to the screen and still create large images.

$$Throw\ ratio = \frac{\mathrm{D}}{\mathrm{W}} = \frac{distance\ from\ lens\ to\ image}{horizontal\ width\ of\ image}$$

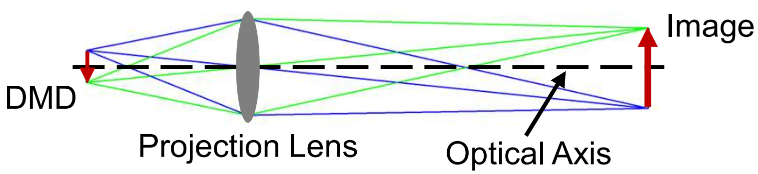


Throw ratio > 2: “long throw”
Throw ratio 1-2: “standard throw”
Throw ratio < 1: “short throw” or “ST”
Throw ratio < 0.4: “ultra short throw” or “UST”

Lens Offset

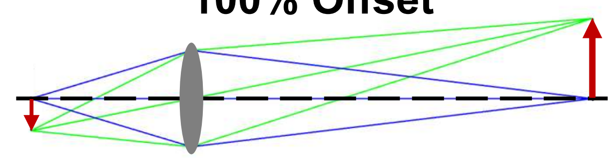
- Offset is a shift of the projection lens relative to the center of the DMD
  - This results in a corresponding displacement of the projected image.
- Offset enables a projector sitting on a table or mounted to a ceiling to display a full image on the wall without any portion of the image being blocked by the nearby surface
- Some projectors are designed with a fixed offset, while others offer adjustable offset by moving the projection lens.
- Larger offsets necessitate an increase in the size and complexity of the projection lens.

0% Offset



- Projected image is centered on the lens, extending equally above and below the optical axis.

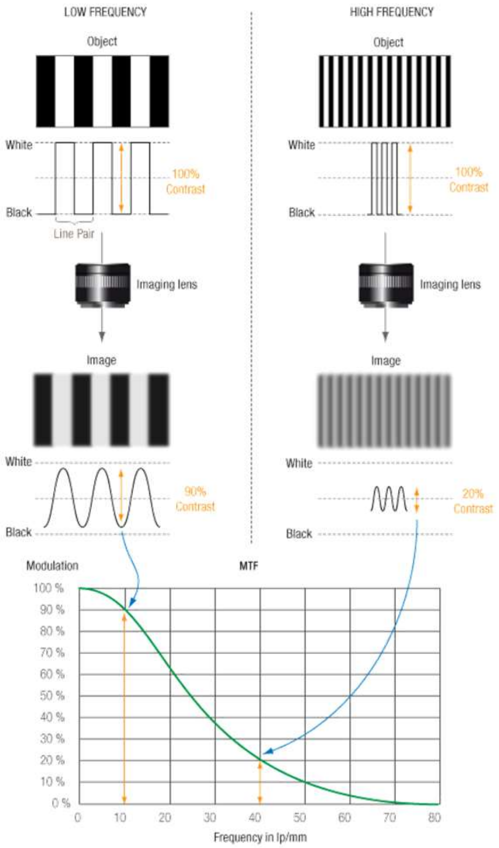
100% Offset



- Projected image is entirely above the optical axis.

Modulation Transfer Function (MTF)

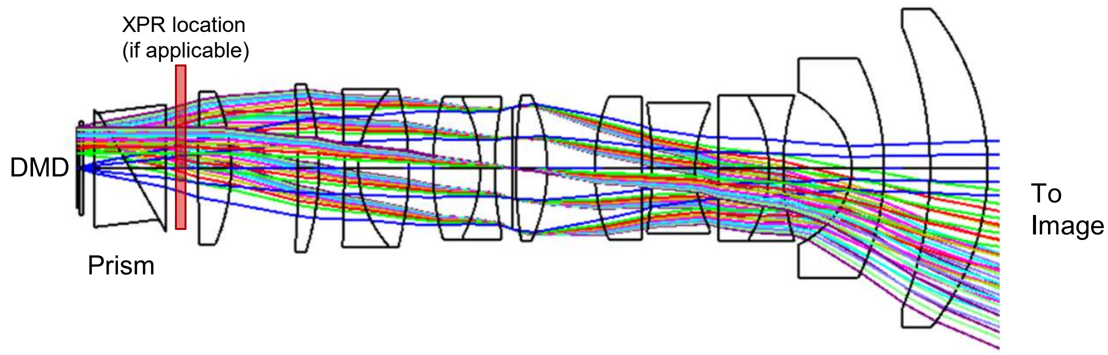
- The MTF is a measure of contrast reduction imposed by an imaging system (projection lens) as a function of spatial frequency in line-pairs/mm (lp/mm)
- It is *the* standard metric to describe lens performance for resolution and contrast
- The spatial frequency of a DMD is determined by the pixel pitch. One line pair = two pixels width
- The highest spatial frequency that can be produced by a DMD or any spatial modulator is one pixel white + one pixel black. This is called the Nyquist frequency.
  - 10.8um pixel = 46 lp/mm
  - 9.0µm pixel = 56 lp/mm
  - 7.6um pixel = 66 lp/mm
  - 5.4um pixel = 93 lp/mm
- Typical requirement for DLP projection lens is 50% MTF at Nyquist by design
  - Some customers often may reduce design to 30-40% MTF to tradeoff performance for cost
  - Must consider opto-mechanical tolerances will reduce MTF
    - Production lenses are often ~20% MTF after tolerances



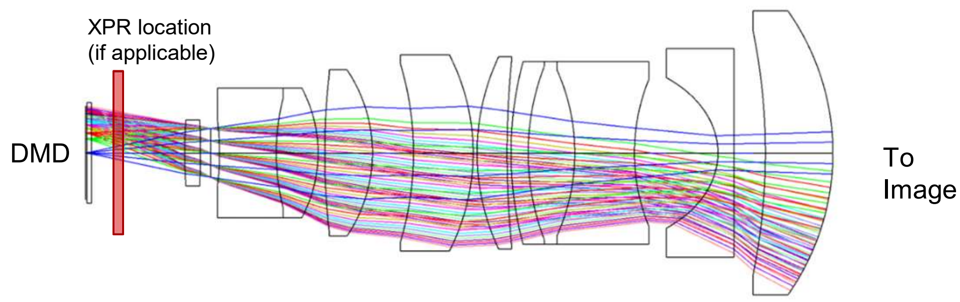
TEXAS INSTRUMENTS

Example Projection Lens Designs

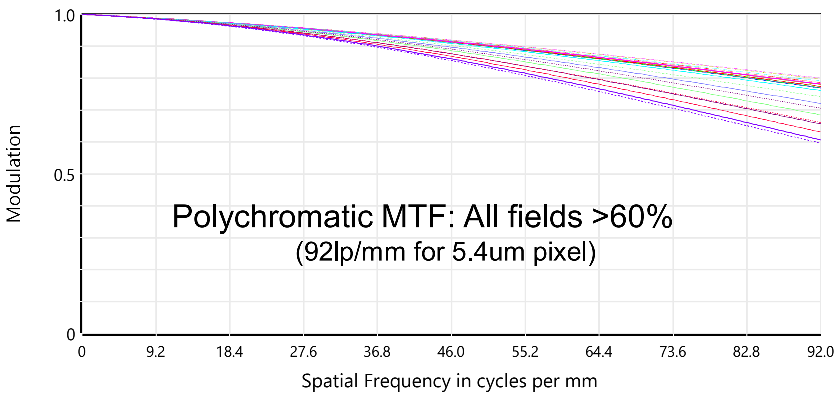
Telecentric



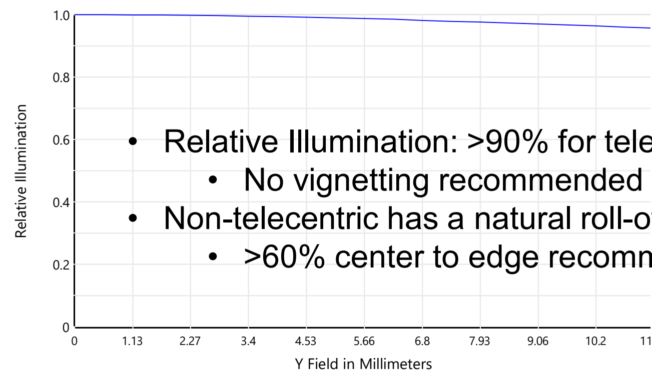
Non- Telecentric



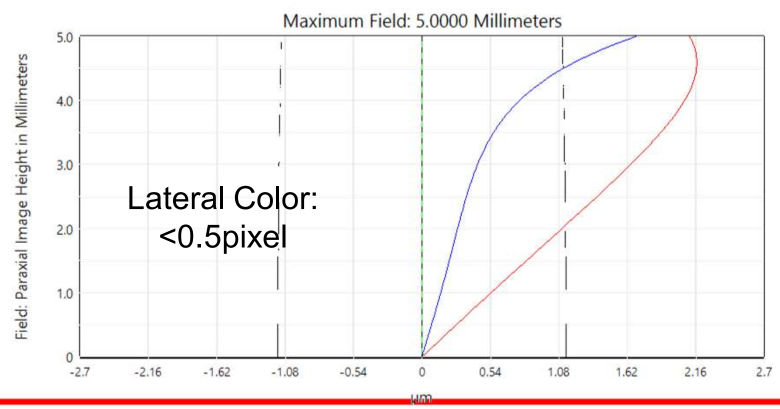
Example Projection Lens Performance



Polychromatic MTF: All fields >60%
(92lp/mm for 5.4um pixel)

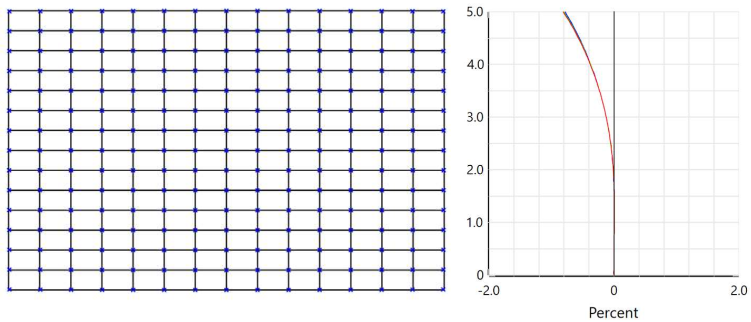


- Relative Illumination: >90% for telecentric lens
  - No vignetting recommended
- Non-telecentric has a natural roll-off
  - >60% center to edge recommended



Lateral Color:
<0.5pixel

Distortion: 0.5%



Resolution Enhancement

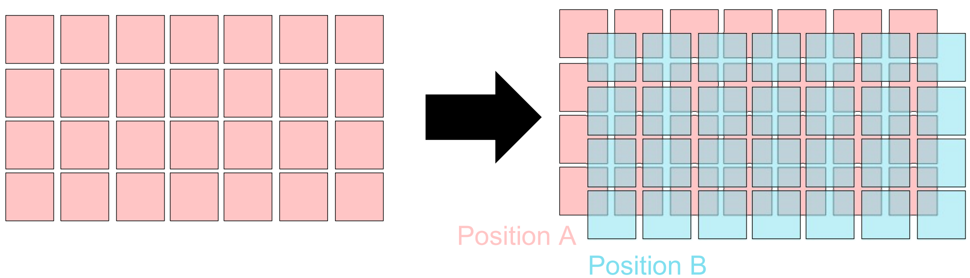
For additional information, refer to:

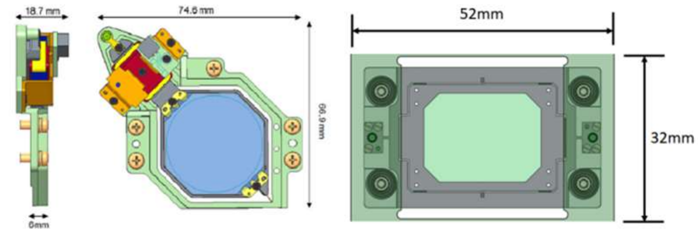
Sing, Molly N., et al. "Super resolution projection: leveraging the MEMS speed to double or quadruple the resolution." *Emerging Digital Micromirror Device Based Systems and Applications XI*. Vol. 10932. SPIE, 2019. https://doi.org/10.1117/12.2512005

What is Super Resolution?

Native DMD Resolution
(2716 x 1528)

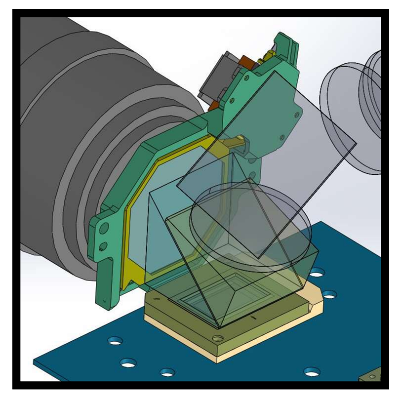
Displayed Resolution
(3840 x 2160)





2-way actuator by
Young Optics Inc.

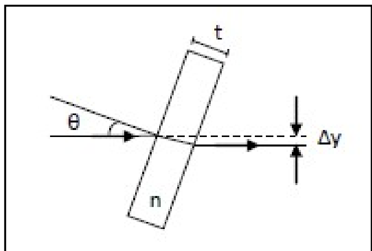
4-way actuator by
Optotune



- Opto-electronic shifting of a DMD pixel using a tilting optical element (actuator) to create 2x or 4x the resolution within a single image frame
- 2-position actuator shift example above
- 4-position actuator shift available also
- https://www.optotune.com/pixel-shifting
- https://www.minaik.com.tw/

Actuator Optical Details

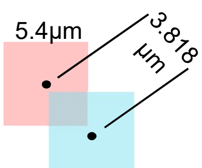
- Transmissive tilted plate used for x & y tilt to displace the beam by ½ or ¼ pixel size
  - Thickness & material will depend on actuator supplier which affects beam displacement
- Actuator plate must be designed into the projection lens optical design
  - placed between DMD and projection lens
- Compatible with telecentric and non-telecentric optics



$$\Delta y = t\sin\theta\left[1-\sqrt{\frac{1-\sin^2\theta}{n^2-\sin^2\theta}}\right]$$

θ = angle of incidence

n = index of refraction of plane parallel plate



Example:

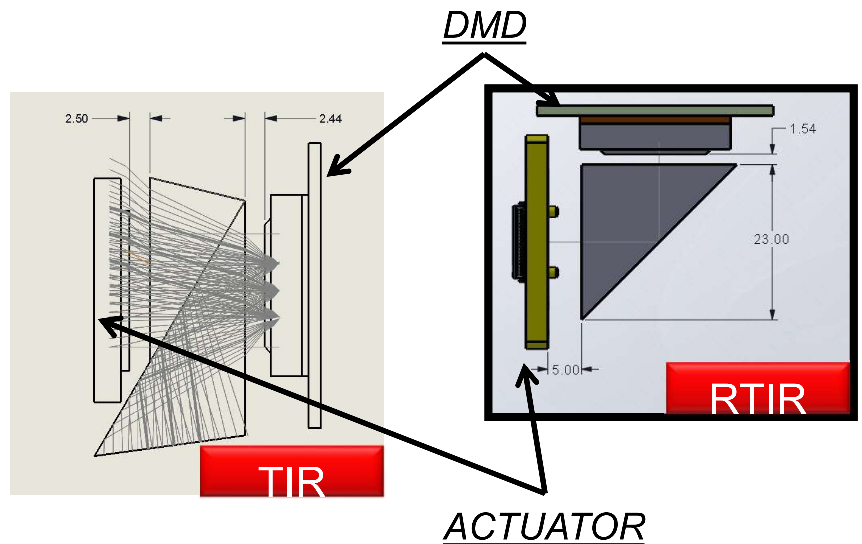
$N-BK7\,(n_d = 1.5168)$

$t = 0.7mm$

$\Delta y = 3.818\mu m$

$\theta \approx 0.9172°$

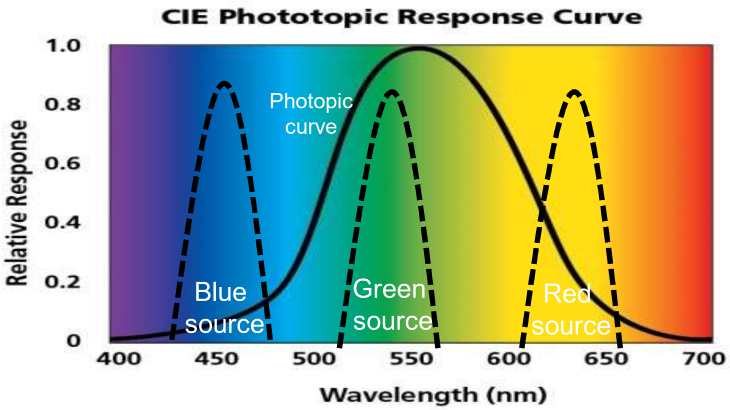
Note: Angle should be optimized

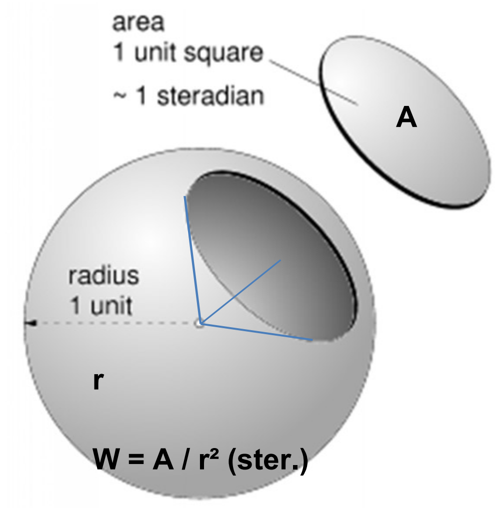


Colorimetry & System Lumens Budgeting

Radiometry & Photometry

Quantity	Radiometric	Photometric	Most useful
Flux	Watt	**Lumen**	Front projection
Irradiance or Illuminance	Watt/m^2	Lumen/m^2 (**Lux**)	Front projection (light falling on screen)
Radiance or Luminance (brightness)	Watt/m^2/ster.	Lumen/m^2/ster. (**Nit**)	Rear projection (perceived brightness)

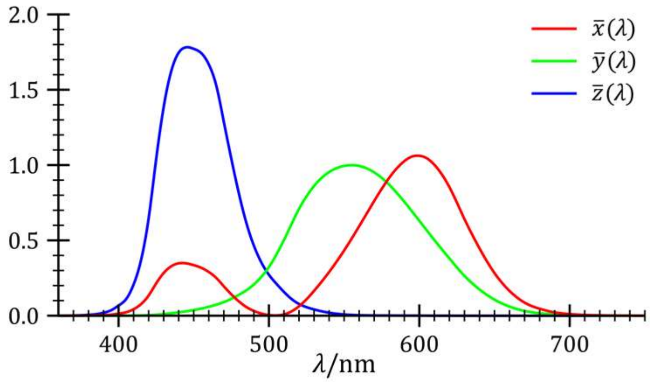




Lumen is a measurement of power weighted by the photopic curve

Photopic (lumens) weighted by eye response

Colorimetry



CIE standard observer color matching functions

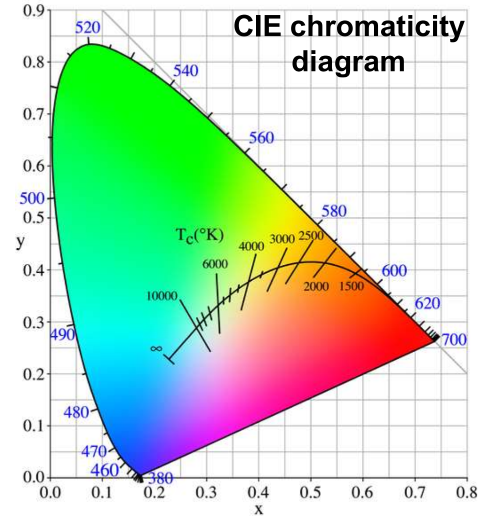
- *Corresponds to how the human visual system perceives colors*
- *Used for color mixing*

$$X = \int_0^\infty L(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int_0^\infty L(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int_0^\infty L(\lambda)\bar{z}(\lambda)d\lambda$$

Where $L(\lambda)$ is the source spectrum



XYZ Tristimulus values can be plotted for primaries such as red, green, blue, yellow, and white using chromaticity coordinates:

$$x = \frac{X}{X+Y+Z}$$

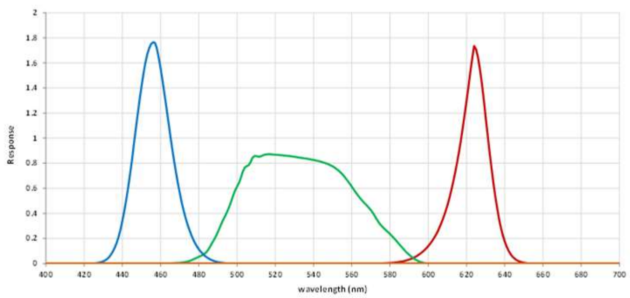
$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

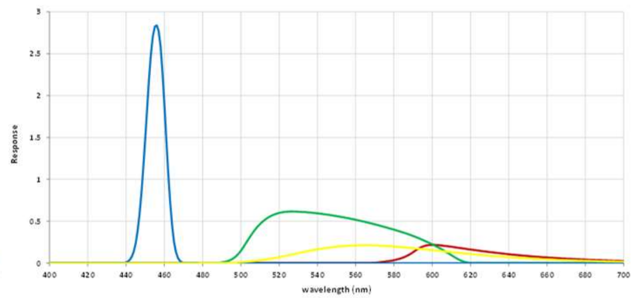
These help determine the color gamut achievable of the projector (see color gamut slide)

Typical Source Spectra L(λ)

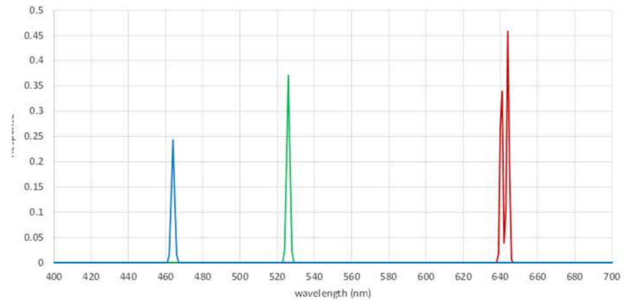
LED



Laser Phosphor

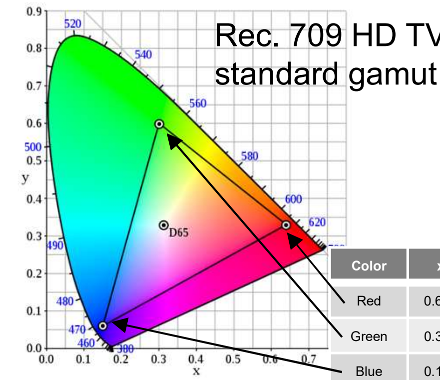


Direct Laser



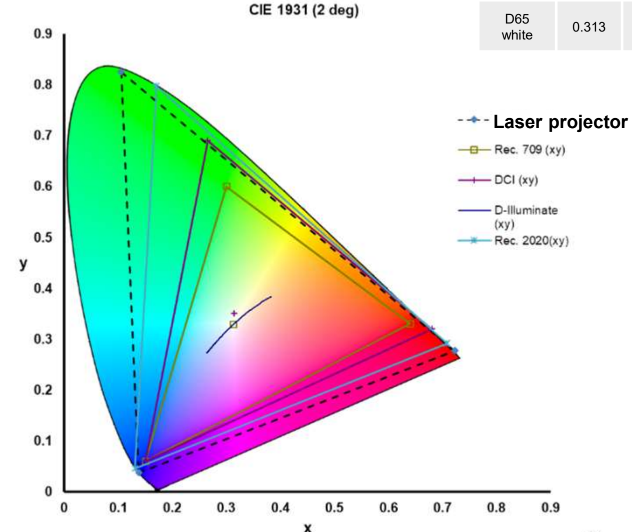
Color Gamut

- CIE 1931 chart represents normalized hue/saturation on a cartesian grid
- Area within the gamut triangle (polygon) represents the set of all colors reproducible by the projector
- Points closer to locus are more saturated or “pure” colors
- Color temperature of “white point” is read from chart
  - Lower color temperatures – red
  - Higher color temperatures – blue
- Laser projectors typically have the widest color gamut



CIE 1931 (2 deg)

Color	x	y
Red	0.640	0.330
Green	0.300	0.600
Blue	0.150	0.060
D65 white	0.313	0.329



Creating a Lumen Budget

- A prediction for the projector lumen output can be made with basic knowledge of the optical parameters

- Process for developing a lumen budget
  - Determine the etendue of the DMD and projection optics and source
  - Determine the fraction of source light sent to the DMD based on etendue (before optical design)
    - Or for more accurate geometric efficiency, use results from optical design raytrace analysis
  - Create a straw man transmission efficiency of the projector system
    - Higher performance coatings will improve system efficiency
  - Calculate the lumen output of the source (color balanced over temperature)
    - Straightforward with LED or laser
    - Laser phosphor requires understanding phosphor conversion and flux density/ thermal quenching as well as spot size blooming (Etendue impact)
  - Combine source output and system transmission for projector lumens estimate

Lumens Budget Example for LED-based system

Projector Optics Efficiency Estimation		Factor		Comment
LED Collimating lenses		0.93		Transmission estimate for 2 lens high angle LED collimator
Dichroic filter plates		0.90		95% transmission per plate (green path)
Fly's Eye Array		0.96		Estimated FEA transmission
Illumination lenses		0.98		2 lenses at 99.5%T per surface
Ilumination fold mirrors		0.99		Silflex fold mirrors (optional). Other reflective materials may be lower reflectance
RTIR Prism Assembly		0.92		Estimated based on previous projector measurements
DMD Efficiency		0.67		Mirror reflectivity + fill factor+ diffraction + coatings (slide 22)
Projection Lens		0.92		Estimated 8 element projection lens at 99.5%T per surface
TOTAL SPECTRAL TRANSMISSION		**0.44**		
	Red	**Green**	**Blue**	
LED collection angle loss		0.93		Limited collection angle of collimator lenses (75° half cone out of 90° lambertian emission)
Collimator to FEA coupling loss		0.90		LED Collimator to FEA coupling loss correction factor (0.8-0.9 typical) - may vary by color depending on path length
Overfill on DMD		0.85		15% recommended illumination overfill - may vary by color due to chromatic aberration
LED Etendue mismatch or Zemax geometric efficiency		1.00		Perfect match assumed for calculation. Efficiency may vary by color in design - careful not to double dip with overfill
TOTAL GEOMETRIC EFFICIENCY	**0.71**	**0.71**	**0.71**	Estimated geometrical throughput (LED to Screen) - calculation
TOTAL SYSTEM EFFICIENCY	**0.32**	**0.32**	**0.32**	Uses these values to combine with white balance source output (incl. duty cycles) to determine projector lumen output

Note: This starting straw man lumen budget assumes R,G and B all are equal in system transmission. Optical design raytrace analysis are required for a more accurate lumen budget analysis.

Thank you for choosing DLP

For additional questions, please post on E2E forum.