Texas Instruments

Lasers & DLP®

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Using Lasers with DLP® DMD technology

Purpose

The DLP® Digital Micromirror Device [DMD] has long been used in video projection systems for commercial and consumer applications. The DMD is also an attractive Spatial Light Modulator for applications that may use monochromatic and/or coherent light sources both inside and outside of the visible spectrum.

The DMD presents some unique advantages and considerations that must be understood for these applications particularly when using coherent or semi-coherent sources with the DMD. When used with such sources the fact that the DMD is a 2D array of periodically spaced mirrors cannot be ignored, rather the diffractive effects can be understood and even exploited.

The purpose of this paper is to present an intuitive understanding of the 2D diffraction properties of the DMD and the advantages and challenges that result.

Understanding Diffraction – an intuitive view

Single Slit Diffraction.

To begin our journey lets consider diffraction from a single slit. We will assume that the length of the slit is much larger than the height "a" of the slit so that the dimension along the slit is not considered. We will also assume that the distance "*D*" to the "screen" is very much larger than the slit width. If the incident light is a monochromatic plane wave then there will be some angles in which the overall light from the slit will constructively interfere and others that will destructively interfere giving rise to light and dark bands on the screen.[*] The following link has a great illustration: Single-Slit Diffraction.

Now let us replace the flat screen with a cylindrical screen centered on the slit and let the distance to the screen be "*R*", the radius of the semicircle. Then for every angle to the screen we can project back to the plane of the slit such that we can now map every

[*] If we take the normal to the plane of the slit opening (also normal to the screen) as 0 degrees and the center of the slit as the origin, then the intensity at the screen will be proportional to

$$\left(\frac{\sin(U\sin(\theta))}{U\sin(\theta)}\right)^2$$

[the "*Sinc*" function where the argument is in $(U\sin(\theta))$]. Derivation of the intensity can be found in numerous texts on slit diffraction angle to "*x*" on a line such that the distance from the origin is given by $x = R\sin(\theta)$.[*] For ease, let $R = 1$ so that $x = \sin(\theta)$. With this simple mapping of angular space we see that *x* ranges from [-1 to 1] as θ ranges from [-90° to 90°]. All values outside of that are non-physical.

The intensity profile of the bands is proportional to:

$$Sinc^2\left[\pi\frac{a}{\lambda}\sin(\theta)\right],$$

which, with the mapping we have chosen simply becomes

$$Sinc^2(\pi\frac{a}{\lambda}x).^{\dagger}$$

If the angle of incidence is changed so that $\theta_i \neq 0$ then the peak of the *Sinc²* profile will move so that it is centered on $\theta = -\theta_i$. In other words the pattern slides over as the incident angle changes so that the pattern is centered on the normal of the incident plane wave.

Therefore the intensity profile is proportional to

$$Sinc^2\left[\pi\frac{a}{\lambda}[\sin(\theta)-\sin(\theta_i)]\right].$$

In the mapped space if we let $x_i = \sin(\theta_i)$ then this becomes

$$Sinc^2\left[\pi\frac{a}{\lambda}(x-x_i)\right].$$

In order to determine how much light goes into each a subtended angle, all of the light that enters the slit must be accounted for. The profile function itself can accommodate any $-\infty \leq x \leq \infty$ but *x* itself is restricted to $-1 \leq x \leq 1$ as previously noted. Therefore we integrate the far field:

$$A\int_{-1}^{1} Sinc^2\left[\pi\frac{a}{\lambda}(x-x_i)\right]dx = \Phi \text{ (total flux at the slit)}.$$

[*] See *Harvey-Shack* "Cosine space"

[†] This function has zeros when $k\pi = \pi\frac{a}{\lambda}x \;\; (k \neq 0)$ so the spacing between minima is $\Delta x = \frac{\lambda}{a}$.

In other words all the light goes somewhere into the space restricted by +/- 90°. This normalization allows us to determine the proportionality constant "*A*" that gives the intensity at each angle.

Multiple Slit Diffraction

If we introduce multiple identical slits so that the distance from slit center to slit center is "*d*" and if the number of slits is very large, then because of phase relationships between the slits light is restricted to very narrow lines called diffraction orders. These orders are located at

$$\sin(\theta) = m\frac{\lambda}{d} \text{ (where } m \text{ is an integer}^{*}\text{)}.$$

As before, changing the incident angle of the light simply slides the orders over to be centered on the principle ray. In other words the 0^{th} order moves so that it is also located at $\theta = -\theta_i$. Now the orders are located at

$$\sin(\theta) = m\frac{\lambda}{d} - \sin(\theta_i) \text{ or } x = m\frac{\lambda}{d} - x_i .$$

The interesting feature of the resulting pattern is that the relative intensity envelope of these orders is just the intensity profile of a single slit. Notice that this is an envelope. Light is only allowed at the order locations but the relative intensity is obtained by the height of the $Sinc^2$ profile at the order location. The following link has a very good illustration: Multi-Slit Diffraction

Since the orders and the envelope move together with changing incident angle, the 0^{th} order and the peak of the $Sinc^2$ envelope are locked together. This means that the 0^{th} order receives more energy than any other order; how much more is determined by the width of the slits, "*a*" relative to the spacing (pitch), "*d*".

Again all of the light must be accounted for but now because of the discrete orders the equation becomes

$$A\sum_m Sinc^2\left(\pi\frac{\lambda}{a}\left(m\frac{\lambda}{d} - x_i\right)\right) = \Phi$$

for all orders such that

$$-1 \le \left(m\frac{\lambda}{d} - x_i\right) \le 1 .$$

In other words, only those orders that lie in the real space [+/- 90°] can receive light.

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* This integer, "*m*", is called number of the diffraction order and can be negative or positive. The order at a given "*m*" is called the "m^{th}" order.

Reflective Diffraction Gratings

Now consider a reflective grating so that mirror faces replace the slits. The incident light (plane wave) is now on the same side as the reflected light All of the previous discussion applies to the grating, but now we can add one more degree of control to the light. As before, the order locations will be determined by the grating pitch, the wavelength and the incident angle. The 0^{th} order simply follows the specular reflection relative to the normal of the grating surface ($\theta_r = -\theta_i$).

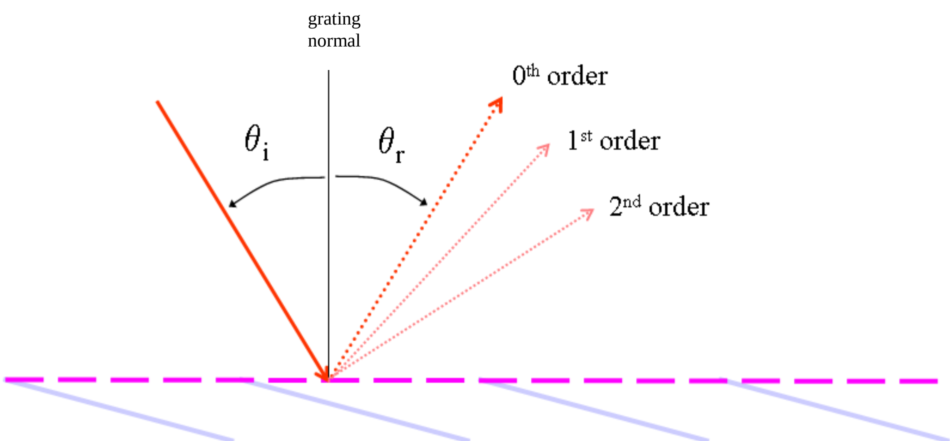


Illustration 1

Now, however, the groove faces can be made with a normal that is not collinear with the grating normal. The result being that the center of the $Sinc^2$ envelope is now decoupled from the 0^{th} order. Rather than being locked to the 0^{th} order the center of the envelope now points in the direction of the specular reflection from the individual groove faces. [i.e. ($\phi_r = -\phi_i$) relative to the groove face normal]

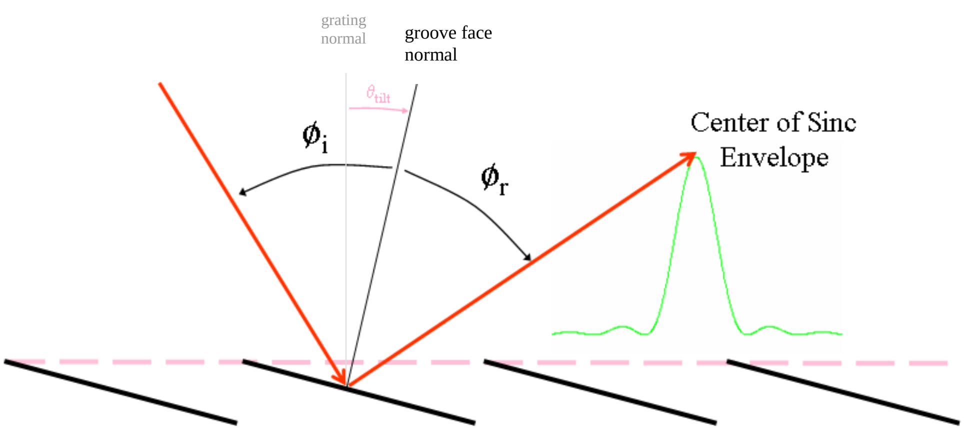


Illustration 2

When the incident angle and the groove tilt are arranged so that the $Sinc^2$ envelope center (peak) lines up with an order, then the order is said to be "blazed".

When this occurs a majority of the energy is directed into the "blazed" order.* When the envelope center falls between orders then energy is distributed into multiple orders. The consequence is that no one order receives a majority of the light. This condition is often referred to as "off-blaze".

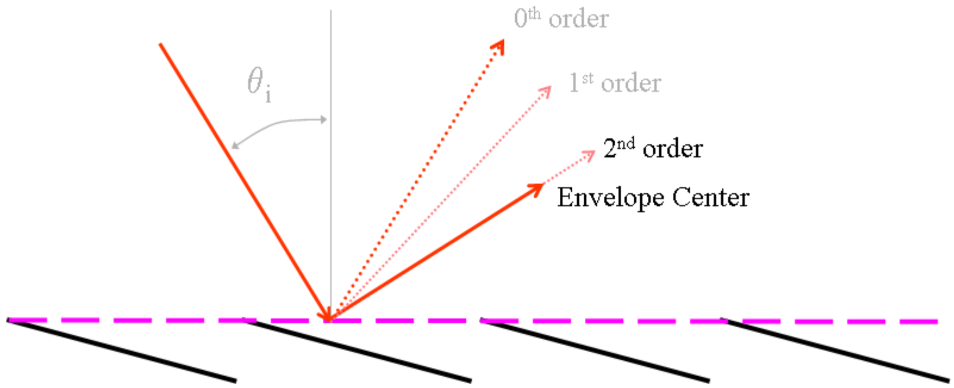


Illustration 3 – The "Blaze Condition" (for 2nd order)

It is important to understand that the location of the 0th order depends only on the incident angle but all other orders depend on incident angle, grating pitch and wavelength. Similarly the location of the Sinc envelope peak is only dependent on the incident angle and the tilt of the groove faces, but the nulls of the envelope are dependent on the width of the slit and wavelength. The consequence is that for all $m \neq 0$ a given order is only blazed for one wavelength.

Another very important but often missed insight is that only the 0th order (and the envelope peak) moves geometrically with changes in incident angle. All other orders are equally spaced from 0th order in the mapped space. This means that as we change the incident angle, if the groove tilt is not 0 then the non-zero orders move relative to the Sinc envelope peak. Therefore it is often possible, in a "non-blaze" arrangement, to change the incident angle so that one of the orders lines up with the Sinc envelope peak producing a "blaze" condition.

Extending to Two Dimensional Gratings

Armed with the understanding of 1D grating diffraction we can extend this same understanding to two dimensions. We will restrict our consideration to a grating with two orthogonal groove systems. Let the new dimensions be a_x and a_y for the face dimensions (mirror) and d_x and d_y for the grating pitches.

* When the blaze condition is arranged so that the incident light and the order of interest are collinear the condition is referred to as a "Littrow" blaze. This condition can allow the same optics to be used for both input and output of the order of interest.

Now orders are no longer lines, but rather, since they are constrained in two dimensions to particular directions the orders become "dots" on our mapped space. These orders are located at

$$\left[m\frac{\lambda}{d_x}, n\frac{\lambda}{d_y} \right]$$

with the (0,0) order at the specular grating reflection and a

$$Sinc^2\left[\pi\frac{a_x}{\lambda}(x - x_i) \right] Sinc^2\left[\pi\frac{a_y}{\lambda}(y - y_i) \right]$$

envelope centered on the specular reflection of the faces. A link showing a 2D (no tilt) pattern can be found at: 2D Grating

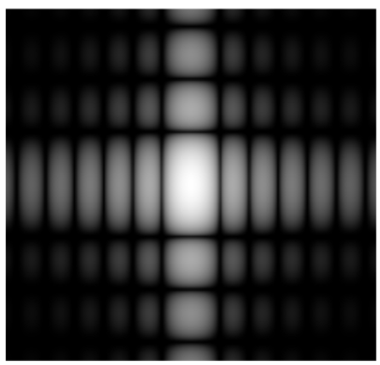
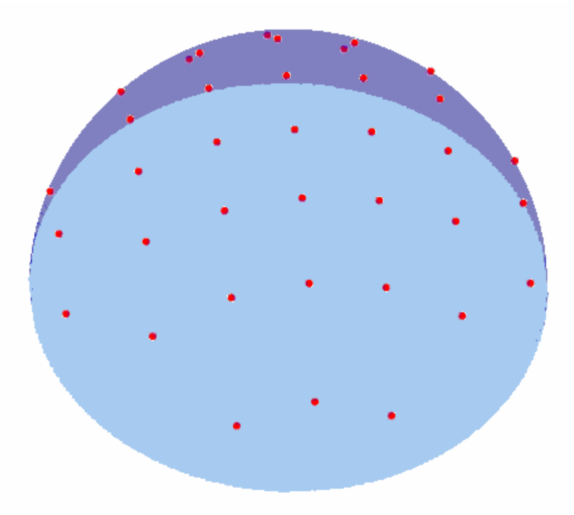


Illustration 4 – 2D *Sinc*^{2} Envelope (gray scale)

Again all the light that that is incident on the array must be accounted for. Some is lost in the fill factor, but the remaining light must go into the real space. As in the 1D case we can renormalize to determine the light going into each order for a given set of geometries, wavelength and incident angle.

The DLP® DMD as a Two Dimensional Grating

DLP®'s DMDs employ square mirrors so that $a_x = a_y$ and $d_x = d_y$ so from here on we will only refer to "*a*" and "*d*". Furthermore, the mirror tilts +/- θ_{tilt} about an axis that runs diagonally on the pixel. The result is that the only orders the envelope can be centered on lie along the line of the $m = n$ orders.



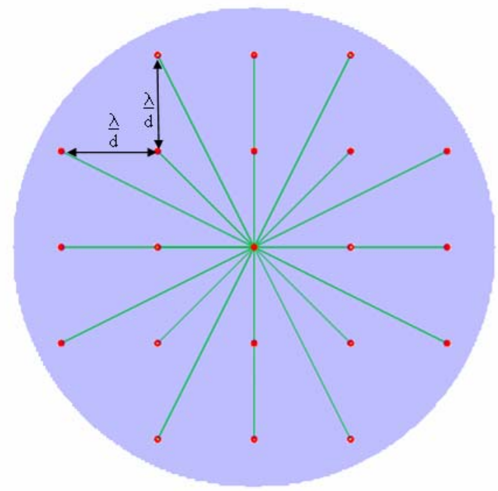


Illustration 5 – 2D hemisphere view of orders

Illustration 6 – View from above (mapped space)

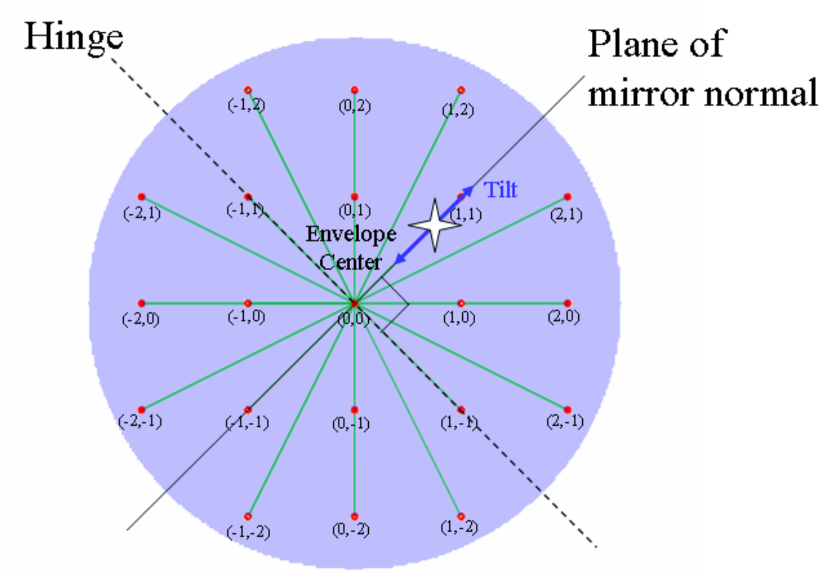


Illustration 7 – View of numbered orders and Envelope center for a DMD

The objective then, for most applications, is to arrange the geometries so that for the wavelength of interest the envelope center lines up with an order. For the DMD the pitch and mirror tilt are fixed. However, it is again possible to move the incident angle to arrange a blaze for a given (*n*,*n*) order. In the following illustration the (*n*,*n*) order is refered to simply as the n^{th} order. The following illustration shows the relationship between incident angle, tilt angle and blaze.

Please notice that along this line $x = y$ so that the Envelope function is falling off as $Sinc^4$. This means that when the DMD switches from on to off the intensity of the orders that were previously blazed have excellent extinction.

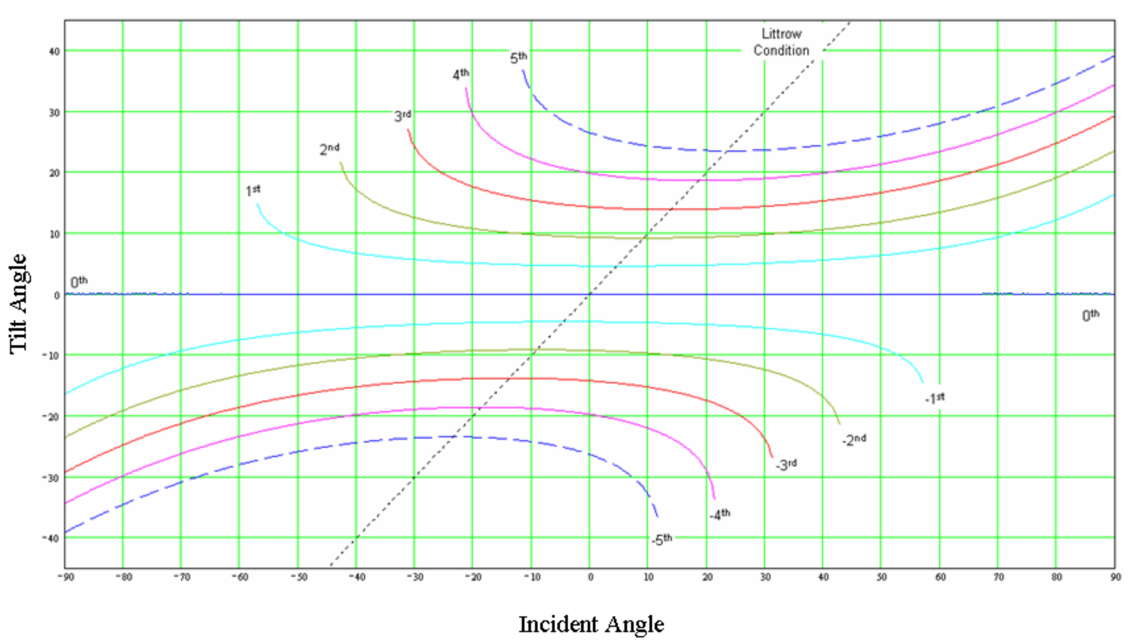


Illustration 8 – Relationship between Incident, Tilt and Blaze
NOTE: the (*n*,*n*) order is refered to simply as the n^{th} order in this diagram.

Notice the special blaze condition (represented by the dashed diagonal line) where the incident angle and the tilt angle are the same. This is known as the Littrow condition and is advantageous when using the same optics for inbound and outbound light.

Advantages and Considerations

Using the DMD with coherent light result in diffraction and consequently these effects must be taken into account, but the diffraction also provides advantages in many applications. Some of these advantages are:

- At large wavelengths (IR):.
  - The blaze condition is fairly insensitive to production variation in tilt angle.
  - The "on" and "off" state blaze orders are separated on the diagonal of the 2D *Sinc* envelope giving an excellent extinction ratio from "on" to "off"[*]
  - Because light is separated into discrete orders, optics can easily be made that gather only the order of interest.
- At small wavelength (UV)
  - Tuning can usually be accomplished by changing incident angle less than +/- 2 degrees
- If the input beam is collimated then the individual orders are also collimated (that is they retain the characteristics of the input beam).

[*] On the diagonal the 2D envelope is proportional to $Sinc^4$ so that orders on this line fall off extremely rapidly in intensity.

There are also some special considerations when using the DMD with coherent light that are a result of the nature of diffraction:

- For a given wavelength and pixel pitch, orders are fixed in direction space by the incident angle alone (switching the mirrors does not move them).
- The intensity envelope of the orders is determined by the shape of the mirrors (square for the DMD) so that individual orders cannot be arbitrarily extinguished without affecting all the other orders.

Conclusion

The DLP® DMD is an attractive spatial light modulator for use with coherent light applications. The reflective nature of our device allows large amounts of light energy to be modulated with a modicum absorbed by the device.