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Projection Lenses in Digital Projectors

By Michael Pate, President, OSCI

The projection lens assembly has a very important job in a digital projector. The projection lens assembly or projection lens must create a high fidelity image of the object or modulator on the screen for the viewer. This sounds easy until we add on all of the performance constraints and opto-mechanical limitations under which the projection lens must operate. Projection lenses fall primarily into two categories, telecentric and non-telecentric projection lenses and in this version of In The Box we are going to discuss

regular projection lenses which are non-telecentric. We will cover telecentric projection lenses next week.

Function of Projection Lens

In digital projectors the job of the projection lens is to create a high fidelity image of the modulator surface or object on the screen or image plane. This function is similar to a projection lens in a slide projector, film projector, overhead projector, and microfilm reader on the object to be projected is different.

In a slide, film, overhead and microfilm projectors the object is transparent just like LCD panels. In DMD and LCoS projectors the object is opaque and reflective. Being opaque and reflective means that the panel must be illuminated and projected from the same side of the panel or object. This often makes the opto-mechanical space in front of a panel very valuable because both the illumination system and the imaging system want to share that space.

The projection lens must capture the light that reflects or is transmitted from the panels and get it to the screen, with high transmission, while magnifying the size of the panel by about 120 to 150 times. The projection lens must be able to get the image into focus when the projector is placed at different distances from the screen. Some projection lenses must also be able to zoom the size of the image because of different distances from the screen and also once resized to focus the image as well.

Typical Projection Lens Design Parameters

Effective Focal Length: 28mm

Back Focal Distance: 42 mm

Throw Distance: 2 – 10 meters

Zoom Ratio: 1.4:1

Field of View: 58 Degrees

Lens Speed or Aperture Ratio: f/2.4

Projection Lens Offset: 150%

Transmission: > 85%

Distortion: < 1%

Polychromatic MTF: > 60% center, > 40% corner at 72 lp/mm

Lateral Color: < 0.5 pixel full field

Effective focal length of a lens is one of the key first order optical design parameters of a lens. It is defined as the distance from the second principal plane to the image plane along the optical axis. In a simple biconvex lens the second principal plane is about in the center of the lens. So if light coming from an object at infinity is imaged by this lens it will focus at one focal length away from this second principal plane. The principal plane can also be thought of as the plane where all of the rays would be refracted to reach the focal plane.

Back focal distance is the distance from the last optical element vertex to the focal plane. This distance is important because it tells the lens designer how much air space or room is behind the projection lens for other mechanical structures.

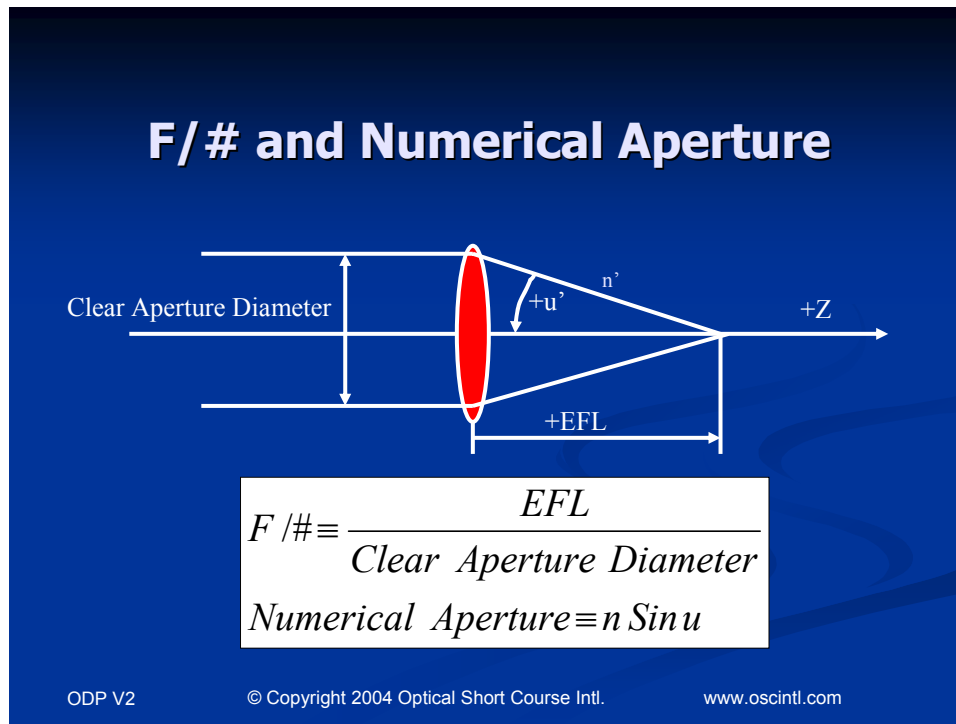


Figure 1. EFL and F/# of a Projection Lens
 From OSCI's Optics of Digital Projectors DVD Course
<http://www.oscintl.com/prod01.htm>

In some cases the relationship between the effective focal length and the back focal distance is very important. In the case where the back focal distance is greater than the effective focal length this class of lens is called a retro focus or inverse telephoto lens type. This class of lens is required with most digital projectors because of the large magnification of the modulator panel. The high magnification in a short projection distance drives the lens to also have a short effective focal length. The illumination from the same side of the modulator and the requirement for TIR and X-Cube type prisms between the modulator and projection lens requires a large back focal distance.

To design an inverse telephoto projection lens there is usually a negative lens or group of lenses that make up a negative group first and then a positive lens or group. We can see that this arrangement in Figure 2 below causes the marginal rays to diverge through the negative group. As these marginal rays are focused by the positive lens group the focal plane is made to farther away than originally because the negative group diverged the marginal rays. The dotted line rays are the original rays if not refracted by the negative group. We can see that the back focal distance is greater than the effective focal length and this puts the lens into the class of objectives called inverse telephoto or retro focus lens. It is interesting to note that many wide field of view lenses fall into this category.

Inverse Telephoto Lens

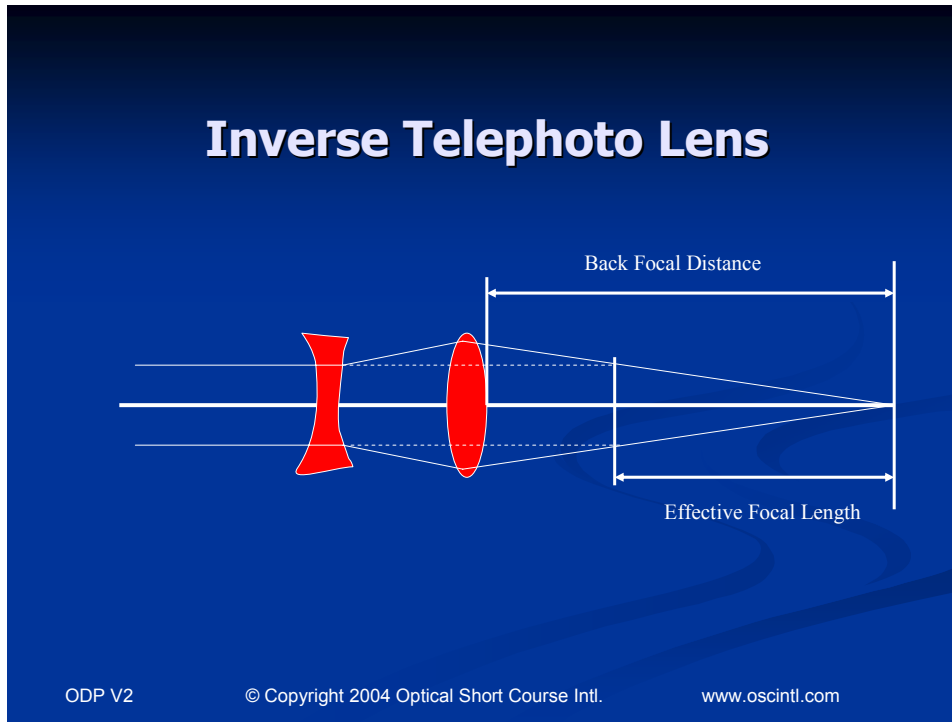


Figure 2. Inverse Telephoto Projection Lens Class
From OSCI's Optics of Digital Projectors DVD Course
<http://www.oscintl.com/prod01.htm>

The throw distance is just the distance from the projection lens outer surface to the screen. This is an important parameter if your projector will be used in different locations where this distance changes. Before you start thinking about projecting a huge image remember you are spreading a fixed amount of light over the projection area that you choose and the larger the magnification gets you will be able to see the pixilation in the image. Bigger isn't always better.

The zoom ratio is just the long focal length divided by the short focal length of the zoom lens. For example if our zoom lens is a 60 to 40 mm focal length range zoom lens our zoom ratio is $60/40 = 1.5:1$. Zoom lenses change their focal length by having two or more elements or groups of elements moving along the optical axis. In the simple case of a two element zoom lens the positive lens or group of lenses is called the variator because its function is to vary the power of the lens. The negative lens or group of lenses is called the compensator and its job is to refocus the lens as the power is changed by the variator. The distances that each of the variator and compensator lenses or groups is non linear and this can be seen by the shape of the cams cut in the cylinders that move the two groups along the optical axis. If you have any interest in precision mechanisms these zoom cam slots are fascinating. Think about how you would make and then measure these is challenging.

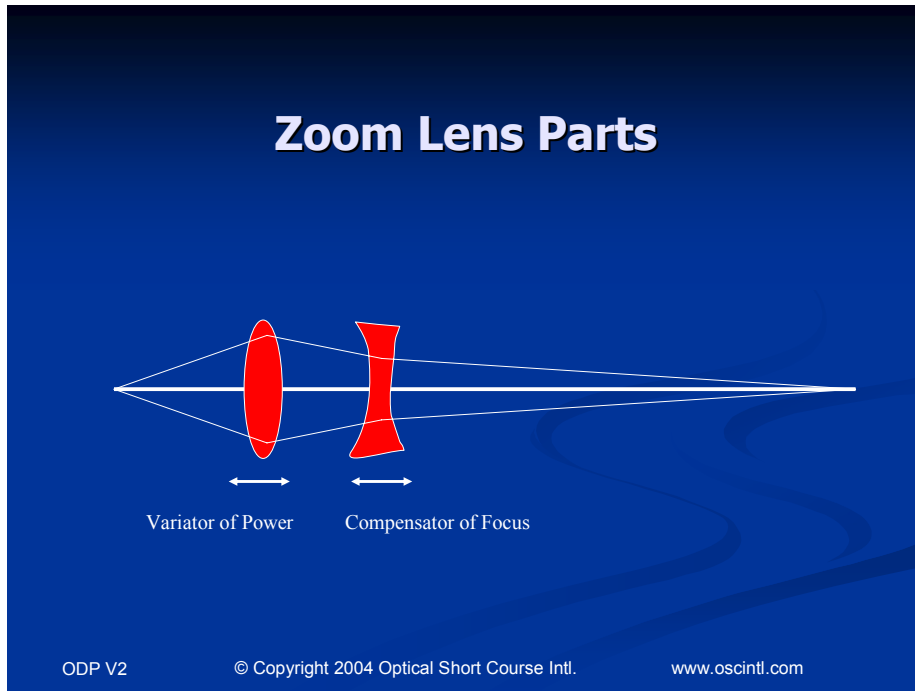


Figure 3. Zoom Lens Schematic
 From OSCI's Optics of Digital Projectors DVD Course
<http://www.oscintl.com/prod01.htm>



Figure 4. Casio Digital Projector Zoom Lens
 Note the cam slots visible in the top of the lens barrel
 Courtesy of Casio

The field of view of a projector lens is chief ray angle in image space over which the projection lens performs well. This is the full angle from one corner of the screen to the diagonal corner of the screen, usually measured in degrees.

The lens speed or aperture ratio is shown in Figure 1 above. The aperture ratio enables optical system designers to determine many lens operation parameters such as lens resolution imaging capabilities, depth of acceptable focus, light gathering ability, and aberration values. The aperture ratio or $f/\#$ of most digital projector projection lenses is fixed by the panel properties. For example in the DMD based projectors with the +/- 10 and 12 degree mirror tilts, this fixes the cone of light that the projection lens can pass at $f/2.89$ and $f/2.4$ respectively.

This is calculated by looking at Figure 1 and looking at the marginal ray angle u' and plugging in the 10 or 12 degree half angle of the cone of light coming from the mirror to the projection lens between on and off state tilts. The relationship between the numerical aperture and $f/\#$ is that the $f/\# = 1/(2*NA) = 1/(2 * \sin u')$.

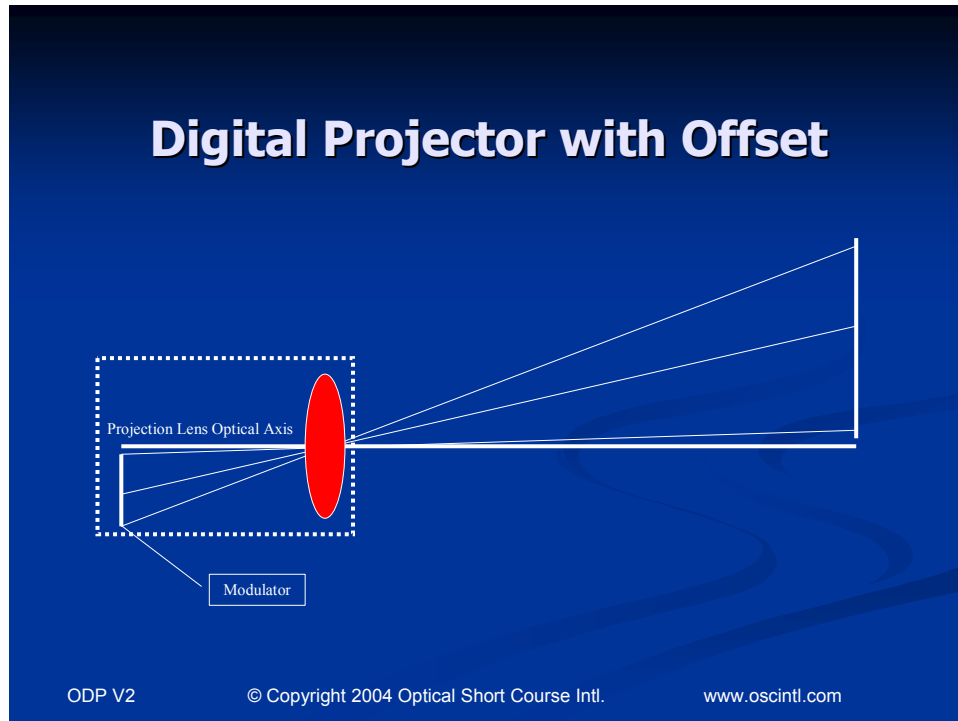


Figure 5. Projector Offset
From OSCI's Optics of Digital Projectors DVD Course
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Projection lenses are typically used on axis because symmetry is good in most cases and it certainly is for optical aberrations to be symmetric around the optical axis of the projection lens. In a digital projector is the modulator is placed on the optical axis of the projection lens the image will be centered on the optical axis of the projection lens also. If we set the projector on a conference table the bottom third of the image would hit the table surface before it got very far from the projector. The same thing would happen the ceiling mounted projectors.

To solve this projection problem the modulators have been offset off of the optical axis of the projection lens. The modulator is still in the same object plane and is therefore still perpendicular to the optical axis it has just been moved off axis or offset. In an imaging system like a projection lens when the object is offset off of the optical axis the image is also offset off of the optical axis in the image plane. Both object and image are still perpendicular to the optical axis. Isn't this a nice convenient geometrical relationship?

150% Offset and Aberrations



Figure 6. Projector Offset
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The offset is measured as the distance from the optical axis of the projection lens to the center of the panel divided by the half vertical height of the panel times 100. Some vendors and companies use different calculation methods so beware of the definition which is being used.

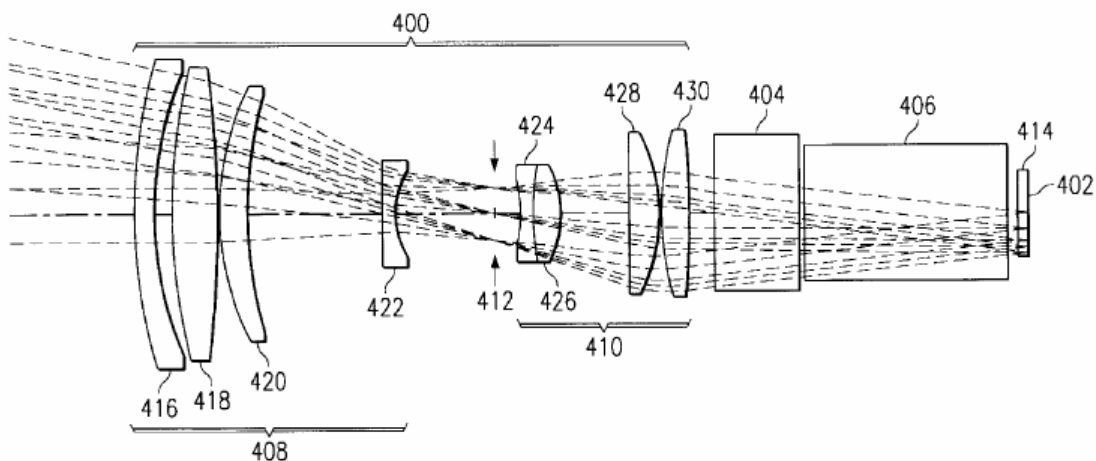


Figure 7. Telecentric Projection lens
 Graphic Courtesy of US Patent US 5,914,818

The optical transmission of the projection lens assembly is a function of the internal transmission of the glass, the thickness of the lens, the coatings on the lens, and the number of lenses. All of these losses are cumulative as the light progresses through the projection lens. Let's take a walk through one optical element and see what happens to our starting 100% value of a light ray.

We start out at 100% and hit the antireflection coating on the front surface of the first lens and transmit 99.75% and reflect 0.25%, not bad. Now we move from the front surface of the lens (but below the antireflection coating) at 99.75% strength to the back surface of the lens with an internal glass transmittance of 99.2%. Next we go from the inside to the outside of the antireflection coating on the second surface of the first lens and it has the same performance as the front surface coating at 99.75%. If we start out at our 100% and then hit 99.75, 99.2, and 99.75% sequentially we will have the product of these transmissions behind the first element or 98.70%

A projection lens assembly like in Figure 7 above has 11 elements or 22 surfaces so if we take $0.987^{11} = 0.866$ or 86.6% optical system transmission for the assembly.

Distortion is an aberration of an optical system that quantifies when a particular part of an object is imaged to a location that is different than predicted mathematically. Many optical designers consider that if an object point is imaged to a different location but has the same spot size then the image is not aberrated or degraded. My definition of a good imaging system is to make a high fidelity image of the object so if a point on the object is imaged to a different location then distortion causes image degradation. OK, off the optical design soap box.

FIG. 4

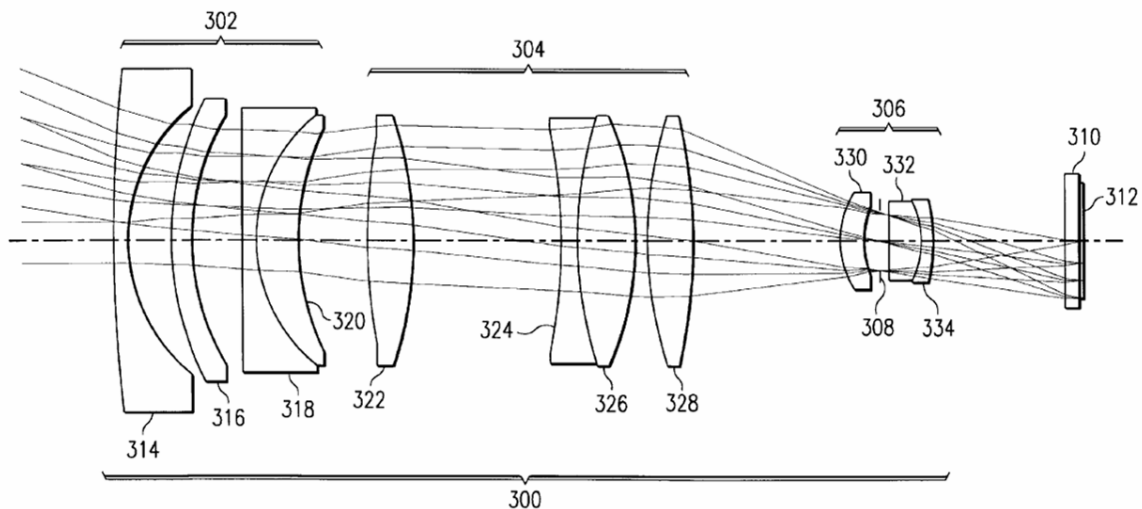


Figure 8 Zoom Projection Lens Assembly
Graphics Courtesy of US Patent 6,008,951

Optical distortion is typically classified into two types depending upon the sign of the distortion and they are called barrel and pincushion. By careful research during the early days of photography it was determined that the human eye on an average photograph could not discern distortion that was less than 1 to 2%. Many optical designer now use a distortion specification of <1% distortion for their projection lens design goals and specifications.

The modulation transfer function or MTF is a measure that some optical designers and many system engineers like to use to quantify the image quality of an optical system. System designer like to use MTF as a performance parameter because they can multiple the MTF of all the components in a system. The product of all of the component MTF's is the system MTF and everybody would like to have only one number to quantify the performance of an optical system.

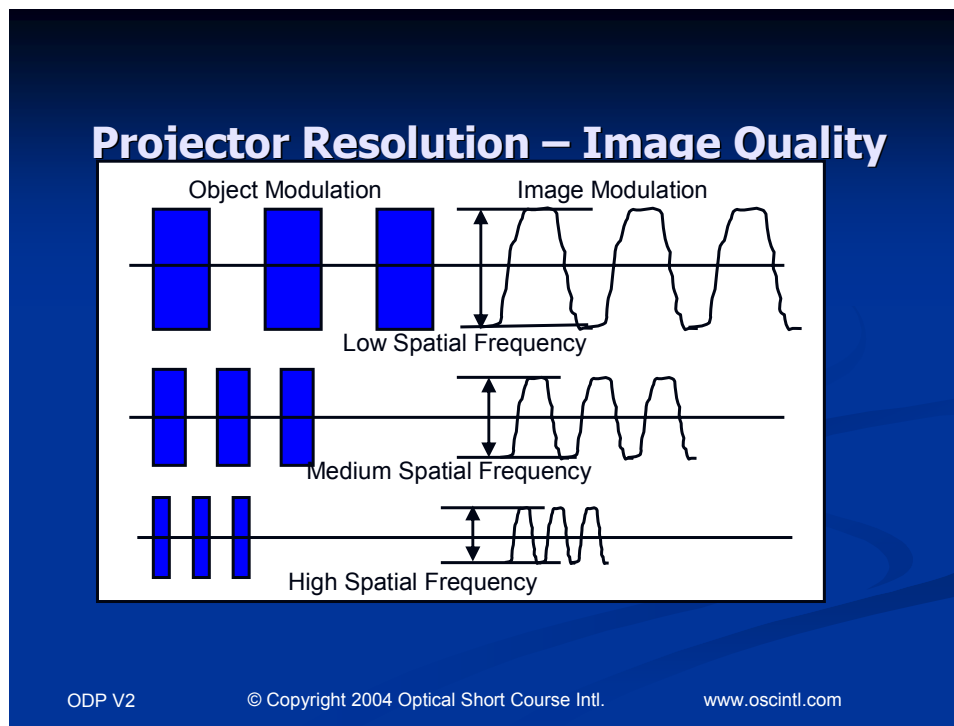


Figure 9. MTF of Projection Lens Assembly
From OSCI's Optics of Digital Projectors DVD Course
<http://www.oscintl.com/prod01.htm>

We can see how the MTF of an imaging system is measured and computed from the graphic illustration in Figure 9. On the left we can see the object which is a series of opaque background and transparent bars. We can see on the right the image of those bars in the image plane of the imaging system. The better the imaging system the higher the modulation of the transparent bar to the opaque background. This modulation is measured as the voltage on the detector or the height of the modulation in the graphic on the right. Higher modulation between the signal from the bar and the signal from the opaque background is better. In typical optical imaging systems the higher the spatial

frequency the lower the modulation. We are showing a square wave function and traditional MTF is measured with a sinewave transmission profile but this is beyond the scope of this article.

MTF can be measured at one wavelength or at several wavelengths called polychromatic MTF. In digital projector system one of the most important spatial frequencies is the spatial frequency of the pixels in the DMD, LCD, or LCoS modulator panel.

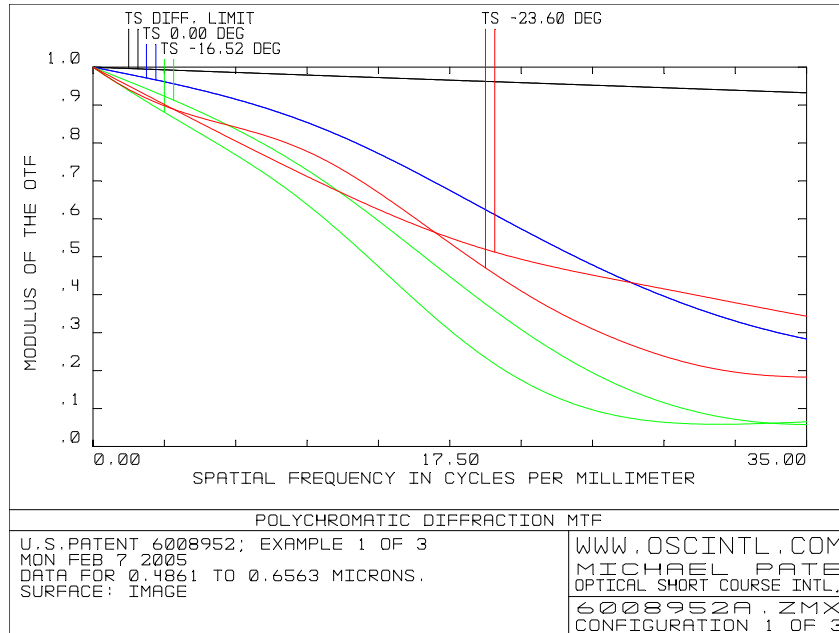


Figure 10. MTF of a Projection Lens Assembly
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<http://www.oscintl.com/prod01.htm>

The lateral color aberration is one of the most difficult to correct and eliminate in a digital projector lens design. We know that all glasses have dispersion which means that they have a slightly different refractive index for each wavelength or color of light. Because we want to view nice vivid colors in our projected images our projection lenses must be corrected to work over the full wavelength range of the visible spectrum. A typical method to correct the color aberrations is to use a crown and a flint glass in an achromatic doublet so all colors come to an acceptable focus.

The lateral color will be the worst at the largest field angles from the optical axis. This point then is typically the corners of the image at the top of the screen farthest from the optical axis of the projection lens. It is a simple test to project sequentially red, green, and blue squares and with a measuring instrument determine where the edge of each square is located. If lateral color is present in the lens design you will see a "chromatic breathing" of the image size.

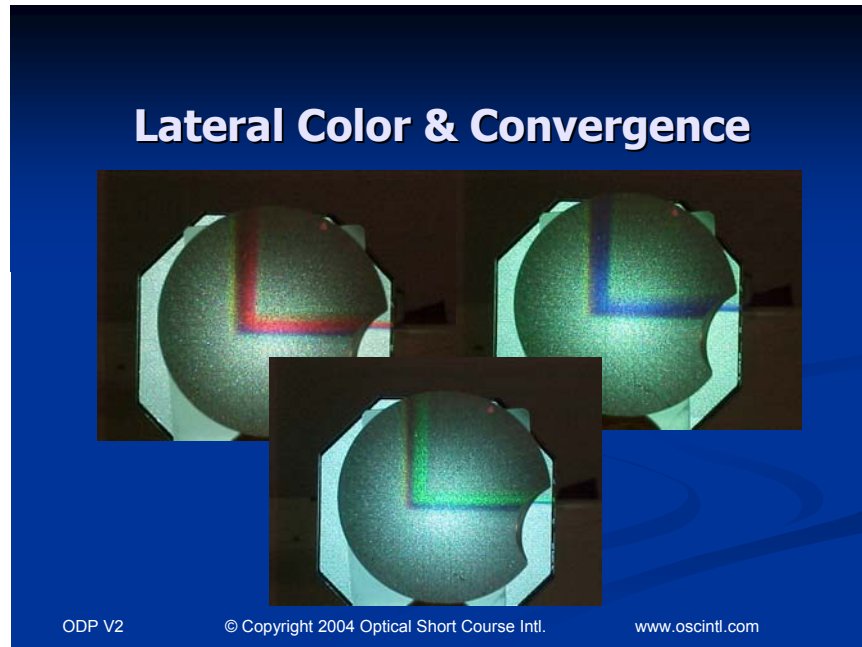


Figure 11. Lateral Color Measurement in Digital Projector Test
 From OSCI's Optics of Digital Projectors DVD Course
<http://www.oscintl.com/prod01.htm>

Some of the advanced techniques being used in digital projector projection lenses is to use one or more “shaped” apertures to increase the contrast ratio of the digital projector in combination with the modulator. Some specific examples of these shaped aperture are shown in Figure 12 below. The aperture labeled Figure 7 shows a straight edge shaped aperture that is designed to block part of the diffracted light from the spatial light modulator microstructure that would have been transmitted through the lens and onto the screen where it would decrease the contrast of the projected image.

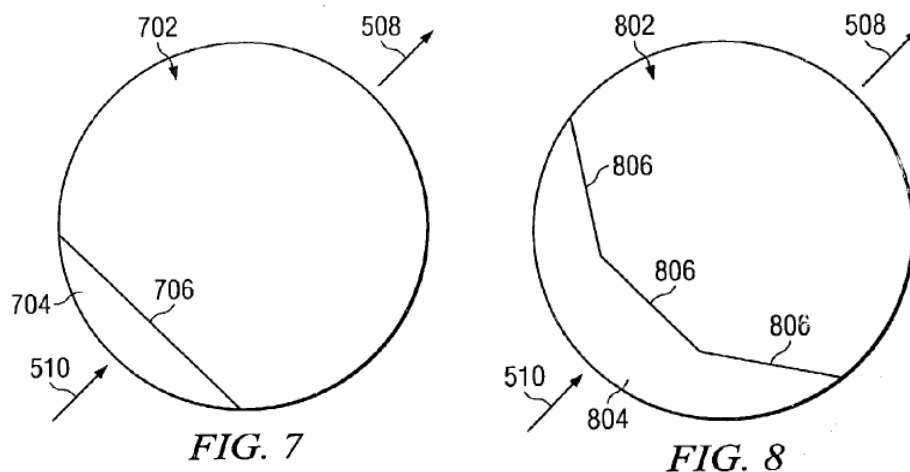


Figure 12. High Contrast Aperture
 Graphics Courtesy of US Patent Application 2003/0147052 A1

The aperture labeled Figure 8 is a more sophisticated shaped aperture that is shaped like a segmented crescent of a moon. This shaped aperture can be at a single plane in the projection lens such as at the aperture stop or can be made from a combination of axial locations. The purpose again is to block diffracted light from the microstructure of the spatial light modulators such as DMD, LCD, and LCoS panels.

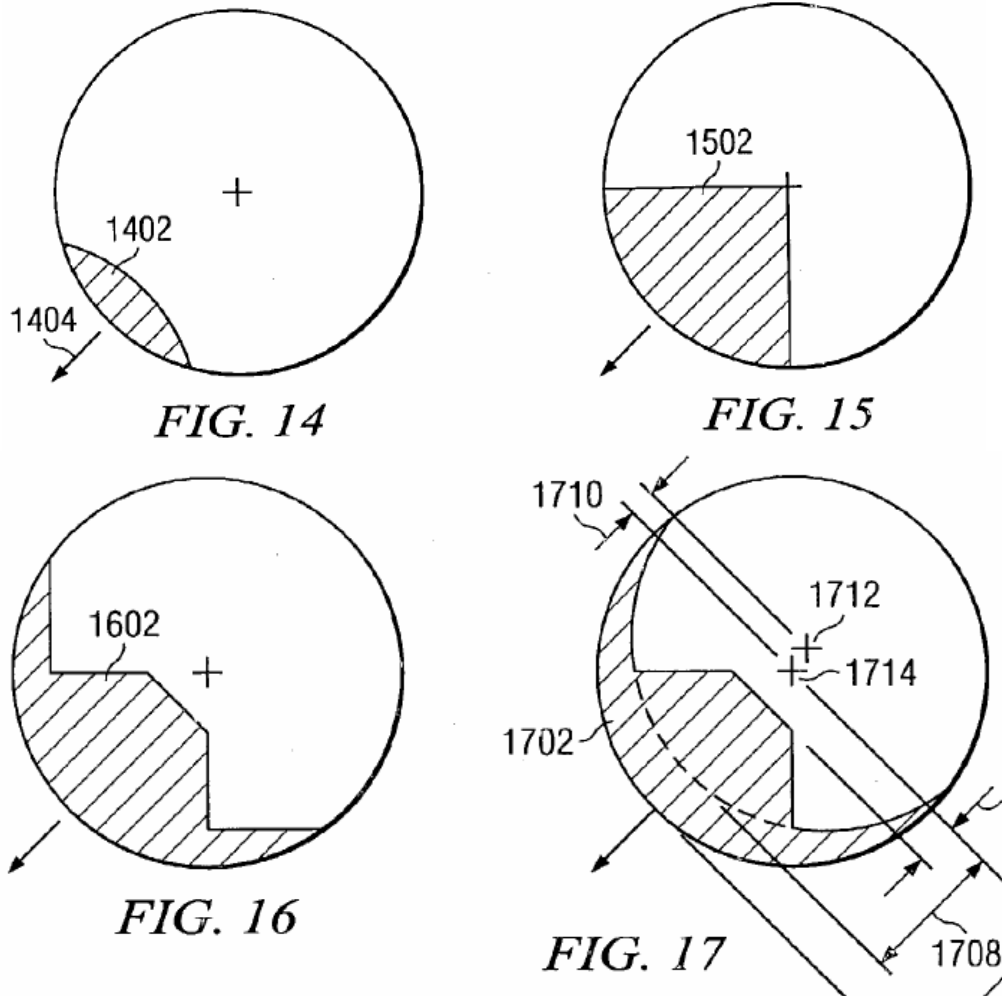


Figure 13. High Contrast Aperture
 Graphics Courtesy of US Patent Application 2003/0147052 A1

In Figure 13 we can see more shaped apertures that are being used to block certain diffraction orders from getting through the projection lens assembly while at the same time maximizing the illumination throughput. These large areas may not block as much of the signal as you might think because of the illumination footprints that are being used on each element in a projection lens with modulator offset.

Summary

We have look at the function and parameter of a digital projector projection lens assembly in this issue. We now know that a digital projector requires are projection lens from a specific category called an inverse telephoto lens. We looked at some details of each parameter and why it is important and what it tells us about the projection lens. We looked at how to test and measure many of these structural and performance parameters of the projection lens. We have also learned about some of the more advanced techniques for improving digital projector performance by projection lens design techniques.

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