52.3: An Improved Polarizing Beamsplitter LCOS Projection Display Based on Wire-Grid Polarizers

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Abstract

MOXTEK has developed a new polarizer technology for the visible spectrum based on the technology of nanometer-scale wire-grids. They have named their technology ProFlux(tm) Polarizers. These polarizers are extremely durable in the LCOS and transmissive light valve projector environment. They also offer very attractive optical performance characteristics as beam splitters in the imaging path, especially for an LCOS-type system. However, since they are plate beamsplitters, they are not a direct replacement for current cube beamsplitters. The proper optical system architecture based on the MOXTEK ProFlux(tm) technology will exhibit significant improvements in image contrast, contrast uniformity, brightness uniformity, and color uniformity. This paper compares performance of conventional beamsplitter cubes with the ProFlux™ beamsplitter. It suggests optical architectures that favor the characteristics of this new beamsplitter while avoiding the problems characteristic of a plate beamsplitter. Test data on polarizers and example system performance will be presented.

1. Introduction

Polarization optics are a fundamental issue in the system design of liquid crystal-based projection displays. The purity of polarization extinction is a key element in color consistency, as well as contrast, across the display. Polarization components also contribute to the overall flux efficiency of optical systems.

LCOS light valves, in particular, are dependent upon optical architectures built around a polarizing beamsplitter. Unfortunately, conventional MacNeille beamsplitters are characterized by poor contrast and transmission uniformity across the angular aperture, with these weaknesses becoming increasingly intolerable as the aperture is increased. With economics driving LCOS panels toward smaller pixel sizes, the resolution requirements drive both imaging and illumination f/numbers toward f/2.0.

Wire-grid polarizing beamsplitters do not suffer as severely from these angular aperture sensitivities, and therefore offer significantly improved optical system performance when implemented in the appropriate architecture. They constitute a technology critical to the continued progress of LCOS and other liquid-crystal projection technologies.

2. Lens Design

Lens design considerations, including aberration control drive the decisions regarding the specific beamsplitter architecture implemented. It is necessary to understand the impact of selecting a particular device on system performance.

2.1 Conventional Projection Lens Design Architecture

Two basic architectures characterize liquid crystal projectors: AMTFT and LCOS based panel systems. The construction of the panels has a significant impact on lens and illumination system design.

2.1.1 AMTFT Liquid Crystal Projection

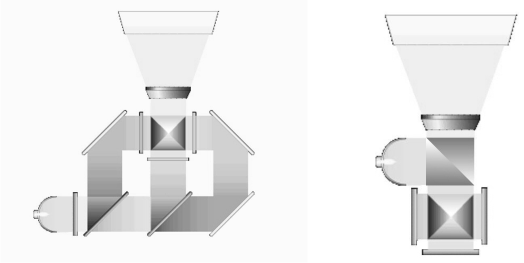

Figure 1a&b - Liquid Crystal Projector Architecture

The Active Matrix Thin Film Transistor (AMTFT) projector architecture (Figure 1a) inherently comprises transmissive LCD panels that place the illumination system behind, rather than in, the imaging path. This architectural constraint has spawned a family of lens forms that incorporate the large block of glass constituting the color combination prism in the back focal region of the lens. This architecture is the basic form of many lens patents, including US Patent #5822129[1] for example (Figure 2).

These systems necessitate a significant amount of back focal distance in order to accommodate the color combination prism, but are driven to lower and lower f/numbers in order to provide the optical resolution necessary to achieve the increasing pixel counts demanded by the market. This combination requires ever-increasing lens apertures that translate into ever-increasing prices for optical components. AMTFT systems also are limited in their irradiance limits due to the susceptibility of the TFTs incorporated into their structures.

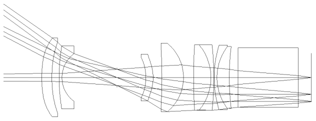

Figure2 – US Patent #5822129, Example 4 of 5

2.1.2 LCOS Projection

The LCOS technology offers relief from a number of limitations, among them flux density, speed, and pixel size. Due to smaller

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pixel sizes, there is potential relief through reduced panel dimensions. However, the LCOS generates another complication.

The LCOS display panel, due to its construction, is reflective in nature and demands that the illumination and projection directions are the same. A prime example of this architecture, implemented in a three-panel configuration, is the JVC DILA projector. This system uses the color combination prism of the AMTFT in a double-pass configuration, but precedes it with a polarizing beamsplitter (PBS) in order to introduce the illumination beam.

The beamsplitter that is nearly universally used is of the MacNeille type. Its function derives from establishing Brewster's condition at the polarization splitting interface. This condition requires that the polarization splitting layer be buried in a high index bulk material so that angles of incidence can be adequately controlled. The limitation of this type of beamsplitter is that its performance varies with wavelength and incidence angle. This performance will be reviewed in more detail below.

Due in part to the evolution of these projectors from AMTFT to LCOS, many designs simply place the MacNeille PBS in the back focal region of the lens, where the combination of low f/number and long back focus drives the size of the imaging lens, as well as the beam splitters, larger and larger.

Upon reflection from the LCOS panel, the plane of polarization is rotated through an angle of up to 90 degrees, proportional to the brightness of the pixel. The polarizing beamsplitter acts as an analyzer, reflecting unwanted light from each pixel back into the illumination arm, and passing the desired light forward to be projected onto the screen by the lens. The optical geometry of this system aggravates the issues of f/number and lens aperture size, as evidenced by the lens of Figure 3. It is apparent that lower f/numbers will greatly impact the apertures of lens elements.

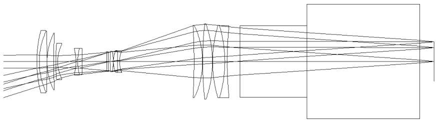

Figure 3 - JP Patent #8297243, Example 1 of 6

If the PBS is introduced elsewhere into the system, however, the negative influence it exerts might be mitigated. Such a system has been suggested by Sugawara in US Patent #5552938[2]. By introducing illumination within the imaging lens system and requiring some of the imaging lens system to act as part of the illumination system (Figure 4), the back focal distance is reduced.

The restriction of this modification is that the angle of rays at the PBS interface must limited such that variation of contrast is limited to acceptable levels. Unlike the system of Figure 3 where contrast is reduced uniformly over the image with decrease of f/number, the system of Figure 4 will alter contrast as a function of field angle and wavelength. The color balance will change from the center to the edge of the display.

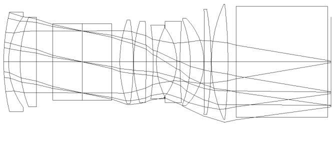

Figure 4 - Sugawara, US Patent #5552938

While it may complicate a lens design somewhat, in neither position does this beam splitter significantly impact the aberration content of the design. Since its surfaces are ideally plane and parallel, and the glass free of birefringence, the cube behaves as an airspace in the design.

Two other forms of polarizing beamsplitter can be employed. Both are plates of glass substrate with a structure on the surface. Because both are plate structures, and must be utilized at an angle to the incoming beam, both are capable of generating astigmatism.

2.2 Astigmatism

For a treatment of astigmatism, one of the primary aberrations of optical systems, the reader is referred to Welford's development[3], or any other good text on optical aberrations. The importance of astigmatism for this discussion is that a tilted plate in a non-collimated beam introduces astigmatism, while an untilted plate does not[4].

2.3 Astigmatism of Plate Beamsplitters

The two variables involved in the contribution of astigmatism in a tilted plate are thickness of the plate and the angle of the plate to the optical axis. The evaluation of the aberration polynomial expression for astigmatism reveals that the aberration will respond linearly to change in thickness of the tilted plate, but will respond as the square to the tilt angle.

There are very few practical situations in which a polarizing beam splitter plate can be employed in anything but a tilted condition relative to the optical axis. In the majority of cases, this tilt angle will be 45 degrees in order for the beamsplitter to best perform its function.

The thickness of the beamsplitter plate is a parameter that can most often be controlled. Pellicles have historically been employed to support beamsplitter structures because their thickness, measured in microns, approaches the limit. Needless to say the thinner the support of the structure, the less astigmatism will be induced.

While the basic orientation of the beamsplitter cannot often be altered because of functional considerations, the convergence of the incident beam can often be controlled in the lens design, albeit at some cost.

The final analysis of the viability of a lens system is rarely dependent on the quantity of astigmatism present. In reality, the Modulation Transfer Function (MTF) is a measure that incorporates astigmatism along with many other aberrations to quickly characterize a lens system.

3. Behavior of Polarizing Beamsplitters

There are three varieties of polarizing beamsplitters that must be considered, although only two will be viable alternatives for the analyzing tasks in display technology.

3.1 Polarizing Plate Beamsplitters

MacLeod describes the construction of an optical thin film plate polarizer in his book[5], but makes the point that the useful wavelength band for the beam splitter is very narrow. In fact, it is so narrow that it is unsuitable for the task under consideration.

3.2 MacNeille PBS

As indicated above, the MacNeille PBS is the most common variety, and is based upon achieving Brewster's angle behavior at the thin film interface along the diagonal of the high refractive index cube in which it is constructed. This device is presently the most favored since its performance is marginally acceptable, and it generates no astigmatism. It does carry a significant cost, however, in both weight and price.

3.3 Wire Grid PBS

The wire grid PBS has been in use for some time in the microwave region where the longer wavelengths make its construction less daunting. However, the MOXTEK Proflux™ PBS is the first commercially available device for the visible portion of the spectrum.

The function of the wire grid is to allow the wave incident on the parallel conductors with polarization perpendicular to length of the conductors to pass through the structure. This occurs because the electric field of the wave can generate no significant current in the conductors in this direction. The polarization parallel to the conductors, however, generates a current in the conductors and imparts energy to the conductors due to their inherent resistance. The accelerating electrons in the conductors radiate in both the forward and rearward directions. The forward radiation cancels the wave moving in the forward direction, and the rearward radiation appears to be a reflected wave[6]. Practically speaking, for one polarization the Wire Grid acts as a lossy dielectric, while for the other polarization, it acts like a metal.

3.4 Test Fixture

Two sets of tests were conducted to compare the performance inherent in the MacNeille and Wire Grid polarizers. The first set of tests were to measure the transmission of the two polarizers as a function of wavelength when placed in the “normal” geometry.

The second test was to evaluate the performance of the two devices in a mockup of a projection illumination system in order to visually compare the extinction performance in the presence of realistic beam geometries. The two devices were placed within an illumination system that permitted collimated beams to penetrate the devices at up to 14.5 degree (f/2.0) cones. The resulting s-polarized beams were viewed after passing through a crossed analyzer in order to evaluate the polarization leakage, or extinction ratio.

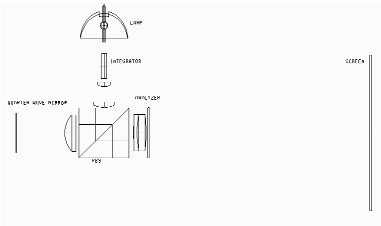

Figure 5 - Test Setup with MacNeille PBS, Proflux is Similar

3.5 Results of Test Fixture

Transmission data was generated for the two systems for both polarizations. Figure 6 depicts the P transmission data. In the case of the MacNeille PBS, the light was incident on the cube face at 0 degrees ±11.5 degrees (f/2.5). In the case of the Proflux™ plate PBS, the light was incident on the structured surface at 45 degrees ±11.5 degrees (f/2.5). At peak extinction, both beamsplitters appeared to be quite good, although the spectral performance was notably different. This can be observed in the plots below.

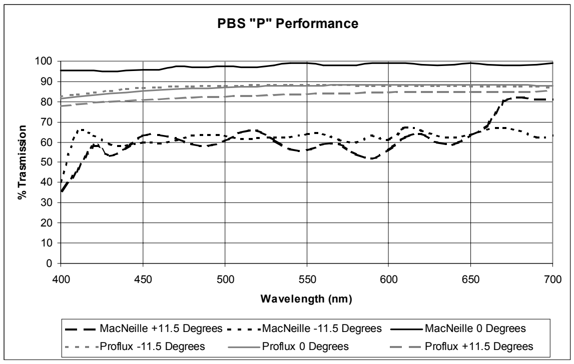

Figure 6 - PBS P Transmission

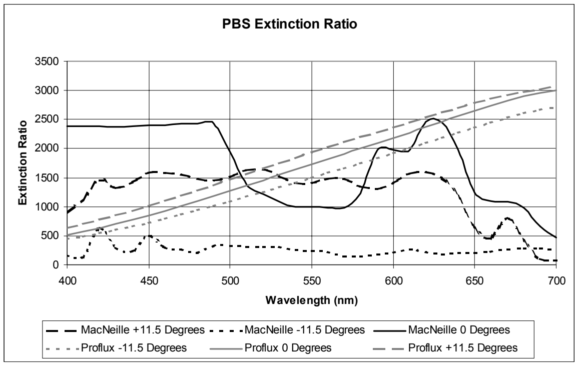

Figure 7 - PBS Extinction Ratio

It is evident from Figure 7 that much greater variation in extinction ratio as a function of angle occurs with the MacNeille beamsplitter than occurs with the Proflux™ beamsplitter, although there is greater variation with wavelength in the behavior of the Proflux™. Even with its spectral variation, however, the Proflux™ delivers performance in excess of 600:1 across the photopic portion of the spectrum, whereas the MacNeille hovers below 500:1 for certain angles. In the design example that follows, the ray angle at the PBS was maintained at a maximum of 14.5 degrees (f/2.0). The extinction ratio was anticipated to be problematic for the MacNeille beamsplitter and the second test was designed to evaluate the extent of the problem.

The visual leakage of the two polarizers is compared in the Figures 8a and 8b. The colors were necessarily converted to grayscale for publication, and the color variation is therefore inadequately represented in the plots. This color variation was relatively extreme in the case of the MacNeille beamsplitter, but was limited to the deep blue portion of the spectrum by the Proflux™ beamsplitter.

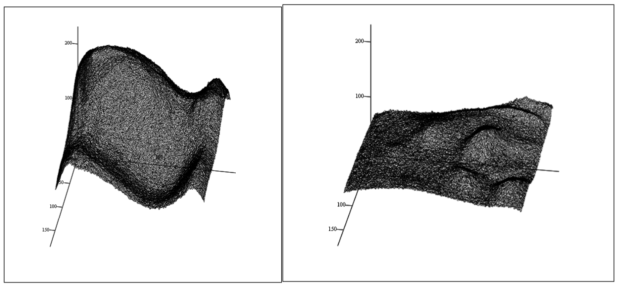

Figure 8a&b – MacNeille and Proflux™ PBS Leakage

The data above were plotted on the same vertical axes in order to enable a proper comparison. An ideal device would provide a flat surface at zero height.

4. A Lens Configuration Utilizing a Plate Beamsplitter

The lens that was used for this lens design example was based upon the Sugawara design. It was chosen because it exhibits an aggressive f/number in image space (f/2.0), and was readily available. It is not necessarily the best form for this application, nor is this lens optimal in every way. It does, however, offer a suitable opportunity to consider the impact of implementing two decidedly different beam splitters in a lens possessing performance characteristic of the genre. The design approach goals included pursuing modestly aggressive field angles of 40 degrees, achromatizing the performance over the photopic curve, ensuring telecentricity at the image plane, achieving f/2.0 performance in image space for an XGA imaging panel, ensuring f/2 angles at the beam splitter. For simplicity, no aspheric surfaces were employed in this exercise. The lens was first optimized for a cube beam splitter. The optimized lens performance is summarized in the plots below.

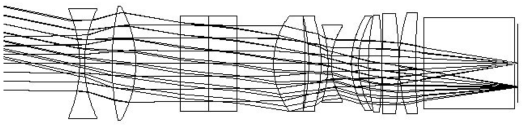

Figure 9 - F/2.0 3-Panel LCOS Projector – PBS Cube

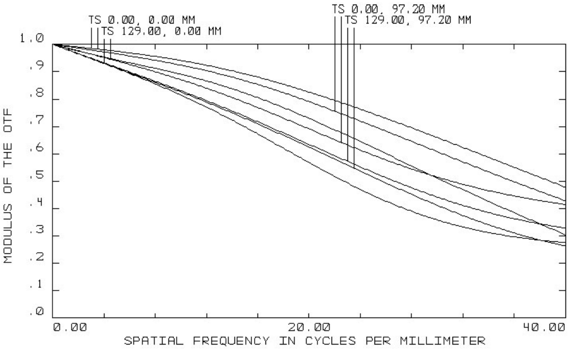

Figure 10 - MTF of F/2.0 3-Panel LCOS Projector

It is apparent that this lens has changed rather significantly in the process of optimization. It is reasonably well-corrected, and the field performance is fairly comparable to the axial performance all the way out to the corners of the image.

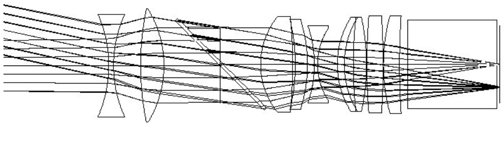

Figure 11 - F/2.0 3-Panel LCOS Projector - Plate PBS

This lens was then outfitted with a tilted plate beamsplitter with dimensions of the Moxtek Proflux™ device. The merit function was modified only as absolutely necessary to accommodate the change in beam splitter, and the lens was reoptimized.

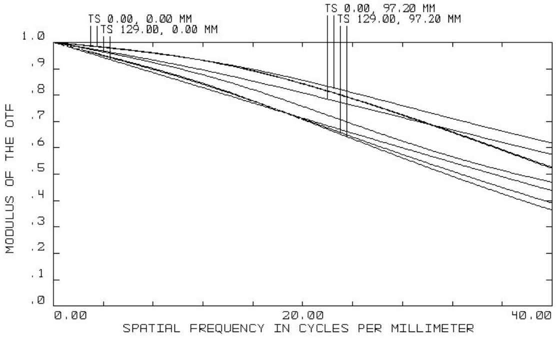

Figure 12 - MTF of F/2.0 3-Panel LCOS Projector - Plate PBS

It is apparent that the lens form has not changed in any substantial manner. However, despite the tilted plate with its associated astigmatism, the MTF of the system has actually improved. The field performance is even more consistent with the axial performance than was the system equipped with the cube beamsplitter.

5. Conclusions

There are two very important conclusions that should be drawn from the testing and the design exercise outlined above. The first is that the wire grid structure is capable of performance superior to the MacNeille-type polarizing beamsplitter. It performs better across the required spectral range, and is more tolerant of large excursions of incidence angles. Furthermore, the implementation of this structure on a plane plate of glass reduces the precision surface count from six to two.

The second conclusion is that any adverse impact of astigmatism introduced to the lens by the tilted plate can be offset by other subtle changes in the lens design enabled by the absence of the high index cube. This offset can permit a lens equipped with the Proflux™ beamsplitter to outperform the MacNeille-based lens in imaging performance.

6. References

[1] Sekine, Atushi, “Projection Lens System,” US Patent No. 5,822,129, Oct. 13, 1998.

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[6] Hecht, Eugene and Zajac, Alfred, Optics, Addison-Wesley Publishing Company, Reading, Massachusetts, 1979.