18.3: *Invited Paper:* The Display Applications and Physics of the ProFlux™ Wire Grid Polarizer

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Abstract

Each year the Society awards the Display of the Year Award to several leading edge display devices or technologies that provide innovative solutions to an information display need. The following paper provides a summary of a 2001 Display of the Year award recipient. The new polarization technology described here enables new solutions to difficult and fundamental problems in the display industry. It is applicable and valuable in all types of Liquid-Crystal (LC) displays or other applications of polarization in information display technology.

1.0 Introduction

Wire-grid polarizers have been known in theory and in certain applications in infra-red and radio for many years. They have not found application in visible optics until now because of the manufacturing challenge involved in producing the nano-structures required. MOXTEK has successfully solved this challenge with a volume manufacturing process capable of producing the required nano-scale wire-grid on many substrate materials. In addition, MOXTEK has developed the physics of wire-grid polarizers to a point beyond that found in the existing literature. The combination of manufacturing process capability and a correct understanding of the physics involved enables a polarizer technology that performs above the expectations of previous researchers in the field.[1]

This new ProFlux™ polarizer brings many advantages to the display industry and to liquid crystal displays in particular. The key characteristics of this technology are: very wide angular aperture with uniform performance, high transmissivity, high reflectivity, heat tolerance, high light flux tolerance, very low depolarization, an extremely thin polarization region, and no organic components. With proper choice of the substrate, it is possible to produce an optic with no birefringence, which is optically flat, or has other desirable characteristics.

2.0 Background

The ProFlux™ polarizer is MOXTEK's first optical product to find widespread application in the display industry. It springs from the company's development of x-ray optics technologies, and in particular, the development of small period x-ray diffraction gratings. This technology began development in the mid 1990's, with the first promising wire-grid polarizer demonstration being produced in 1998. The years between 1998 and 2001 were spent in perfecting the manufacturing technology, building a pilot manufacturing line, and working with key members of the display industry to perfect the optical characteristics of the ProFlux™ polarizer.

The characteristics of the ProFlux™ wire-grid polarizer make it a superior choice for any application in liquid-crystal-based projection displays. Key uses include polarization recovery and use as a polarizing beam splitter and image combiner. In projection displays, ProFlux™ eliminates the problems of polarizer heat loading limitations, skew-ray depolarization, limited angular aperture, and thermal stress birefringence. This critical technology enables LCOS and transmissive panel projection approaches to overcome basic limitations in brightness and optical efficiency.

The ProFlux™ wire-grid polarizer is also useful in a variety of direct view applications. The key application here is the insertion of the wire-grid polarizer into the liquid crystal cell as the back polarizing reflector. In addition, the wire-grid can be used as the rear electrode and as an alignment structure for the liquid crystal. This application is enabled by the very thin structure of the wire-grid, and the compatibility of the polarizer and its manufacturing process with the LC cell manufacturing process and operating environment. Application of the ProFlux™ technology in direct view displays enables high resolution ambient-lit and transflective LC displays, improves contrast, increases viewing angles, and increases light efficiency and apparent brightness.

3.0 Technical Discussion

The physics of the ProFlux™ wire-grid polarizer is different from the common polarizers which are familiar to the industry. In order to use this new polarizer effectively in information displays, it is important to understand the basic characteristics of a wire-grid polarizer.

The most common explanation of the wire grid polarizer is based on the concept of conduction along the individual wires but not across the wire-grid. The electric field of the incident electromagnetic radiation interacts with the wires to cause electrons to oscillate along the wires, but not across the wire-grid. Since electrons re-radiate energy as they oscillate, they absorb energy only from the E-field parallel to the wires and thus create a reflected wavefront for only the one polarization. Because the E-field perpendicular to the wires cannot interact with electrons, this polarization is transmitted through the polarizer undisturbed.

This physical model for a wire-grid polarizer is useful but too simple to help us fully understand the optical behavior of the polarizer. A much better intuitive model is based on the concepts of effective media and form birefringence. Essentially, the optical

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behavior of a nanostructured material is equivalent to that of a new material with optical properties determined by an average of all the materials in the nanostructure.

Because the wire-grid is extremely sub-wavelength (approximately 140 nm period vs. 420 nm period for blue light, or a ratio of 3:1), the interaction of light with the grid structure can be understood as an interaction of light with an anisotropic thin film. In other words, the grid structure is essentially a birefringent thin film with an optical index along the wire direction which is substantially that of the wire material, and an optical index perpendicular to the wires with the properties of a transparent but slightly lossy dielectric. This intuitive model for the wire-grid immediately leads to a number of useful insights.

3.1 Optical Performance Characteristics

The first insight is that performance of the polarizer will obviously depend on wavelength, with the longer wavelengths performing better than the shorter wavelengths. This occurs because the longer the wavelength is with respect to the period of the grid, the more the behavior becomes equivalent to that of a birefringent thin film without dispersion. This behavior is demonstrated in Figure 1, which is a typical performance curve for a wire grid polarizer. Notice that the contrast increases from blue to green to red, indicating the polarization effect of the wire grid becomes more effective at the longer wavelengths.

Using the model of the polarizer as a birefringent thin film, it is obvious that changing the wire-grid structure in various ways will change the optical properties of the equivalent birefringent film and therefore the expected optical performance. For example, the transmission behavior of a wire-grid polarizer will be similar to a single dielectric film, with a maximum and minimum transmission which depends on the film thickness, optical index, and angle of incidence. The broadly peaked transmission performance shown in Figure 1. is due in part to this thin-film behavior. Therefore, a single wire-grid polarizer cannot be fully optimized for use both at near normal incidence and as a polarizing beam splitter with an incidence angle at 45°.

Another point which is clear from this simple model is that the optical performance will be affected by the behavior of the substrate underlying the wire-grid, just as the performance of any optic is determined in part by the interaction of the substrate with the overlying optical films. For example, the substrate Fresnel reflections will be intermixed with the polarized reflections from the wire-grid. This effect works to reduce the contrast in reflection because it is difficult to fully suppress these substrate reflections over any appreciable bandwidth. For this reason, reflection contrast over 100:1 is difficult to achieve except in a narrow band.

These few examples make the point that ProFlux™ performance is a trade-off between competing concerns. For example, the best transmission performance requires consideration of the thin film behavior as well as the polarizer behavior. These two constraints may not be compatible with achieving the optimum contrast at the same time. In general, ProFlux™ polarizers have transmission performance ranging from approximately 85% to 92% while the contrast ratio will range from 100:1 to over 1000:1. Of course, the highest contrast requires a trade-off in transmission and vice versa. MOXTEK has developed a family of ProFlux™ polarizers to meet the various needs of the display industry because some applications benefit from high contrast at the expense of transmission while others require the highest transmission at the expense of contrast.

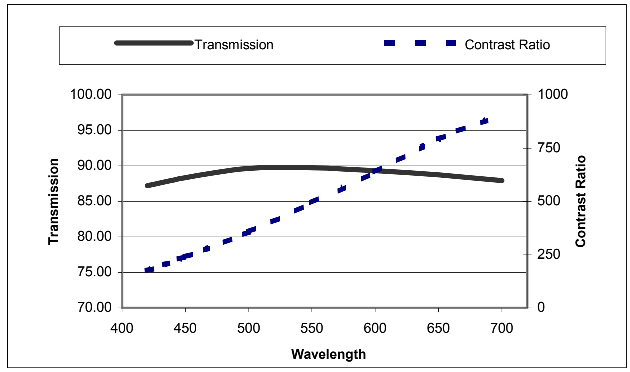

Figure 1. Example Polarizer Behavior.

A key performance characteristic of the ProFlux™ polarizer which can be understood through consideration of the birefringent film model is the excellent performance at large angular apertures. Most polarizers suffer from an effect called skew-ray depolarization. This problem is most pronounced in thin-film cube beamsplitters, but sheet polarizers also change performance significantly at large incidence angles.

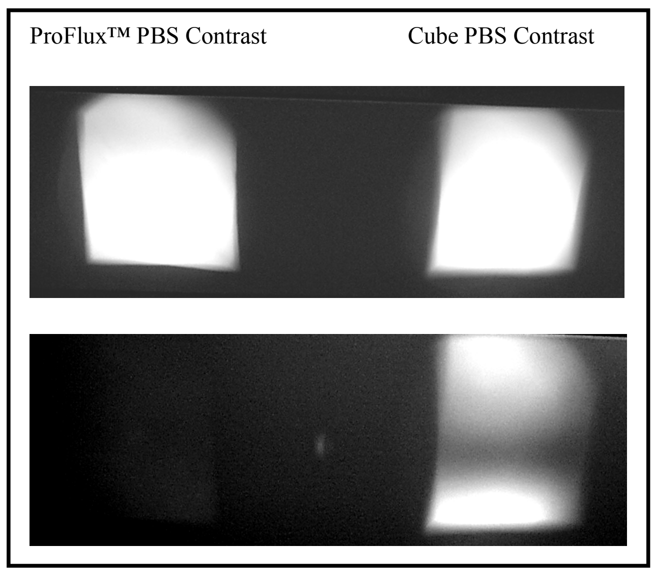

Figure 2. Comparison of Skew-ray Depolarization

Skew-ray depolarization is created by the geometry of the polarization interaction with the incident ray. At large angles, the polarization mechanism in sheet polarizers becomes ineffective, while the polarization mechanism in cube beamsplitters results in a significant rotation of the axis of polarization at the edges of the cone with respect to the center.

The ProFlux™ polarizer does not suffer from this problem to a significant degree. The polarization mechanism of the wire-grid retains its effectiveness up to large skew angles, while the fact that the wire-grid is fixed in space means that the rotation of the polarization axis which occurs for a cube beamsplitter does not occur for the wire-grid. This difference is demonstrated visually in Figure 2. in which a simple optical system is used to compare the aligned and crossed state for a ProFlux™ PBS and a HELF cube PBS at f/2. In this figure, it is obvious that the wire-grid outperforms the cube beamsplitter.

3.2 Durability in Extreme Environments

Because the ProFlux™ polarizer is an inorganic structure, consisting of glass, standard optical thin-film materials, and aluminum, it is extremely durable. Extreme durability is a key advantage of this new polarization technology. It meets all the standard requirements of the display industry for optical components. The standard test conditions which MOXTEK uses in qualifying its polarizer products are given in Table 1. below.

MOXTEK is especially pleased to draw attention to the ability of the ProFlux™ polarizer to withstand an accelerated humidity test. MOXTEK has developed two thin-film overcoating processes which protect the polarizer from the corrosive effects of long-term

Table 1. ProFlux™ Standard Reliability Tests

Reliability Test	Description
High Temperature Static Life	Room Atmosphere 200°C for 1500 hours
Aluminum Adhesion	Military Standard scotch tape test on aluminum MicroWires™
High Flux Test	Philips UHP 150 Watt lamp focused to 7,000,000 lux on MicroWire™ surface for 600 hours.
Temperature Cycle	-40°C to 60°C at RH 85% for 200 cycles.
Temperature/ Humidity	60°C at 85% RH for 500 hours.
Thermal Shock	Liquid Nitrogen to boiling water (-196° to 100°C within 3 seconds.

exposure to high humidity. The standard treatment is applied to all of our polarizer products. This treatment does not cause any measurable change in the performance of the polarizer. In addition, we are able to offer a highly hydrophobic polymer thin film coating that provides added protection for the most extreme environments. This polymer coating has been tested for durability under high light intensities covering the IR to the UV and no degradation has been found.

4.0 Applications

The ProFlux™ polarizer is useful in a variety of applications in the display industry. In particular, it is a critical, enabling component in (LC) projection displays and LC direct view displays. These applications are enabled by the unique combination of heat tolerance, flux tolerance, unlimited operational lifetime, and outstanding optical performance found in the ProFlux™ polarizer. Recommended applications include polarization recovery, the illumination stage, and the imaging stage of projection display systems. For example, OCLI and

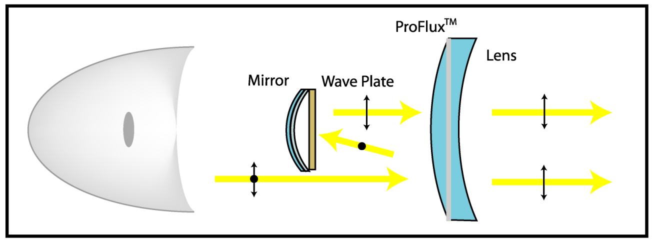

Figure 3. Polarization Recovery Concept

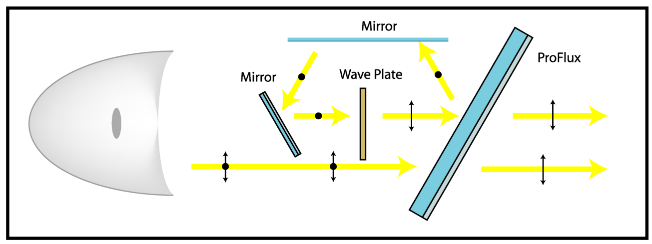

Figure 4. Polarization Recovery Concept

Advanced Digital Optics presented a polarization recovery concept based on light pipes that is enabled by a ProFlux™ polarizer. Figure 3 and Figure 4 outline other concepts that may be useful. A more complete outline of the potential applications of the ProFlux™ polarizer in polarization recovery is given in MOXTEK's patent portfolio, as outlined in section 5 of this paper.

A common application in the illumination stage of 3-panel LCOS systems is as the pre-polarizer at the input to the ColorQuad™ color management system. ProFlux™ is also ideal as a high durability pre-polarizer for 3-panel transmissive projection systems. Use of ProFlux™ polarizers in these areas enable higher brightness, smaller apertures, and longer lifetime than the polarizers being replaced.

MOXTEK is pleased to introduce in this conference an optically flat polarizing beam splitter. This product has been designed for use in LCOS projection display systems. It has performance comparable to the PBS02 polarizing beam splitter currently in production, but is flat to 3 λ per inch. This new PBS enables an elegant single panel design as shown in Figure 5. MOXTEK expects that single panel LCOS projection systems of this type will be very common within 2 to 3 years.

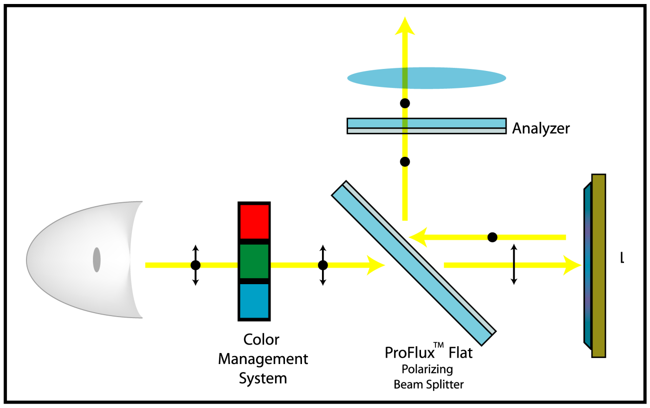

Figure 5. Single Panel LCOS System Concept

5.0 ProFlux™ Polarizer Intellectual Property

MOXTEK filed a number of patents during the development of the ProFlux™ technology. These patents focus on the nanostructure details required to produce a high performance polarizer, and on the applications enabled by the unique properties of the wire-grid polarizer. To date, 9 US patents have been granted, and additional US and foreign patents are pending. The granted US patents are listed in Table 2. MOXTEK employs the structure patents that have been granted, and additional patents pending in this area to defend its market position.

6.0 Current Status and Future Developments

The ProFlux™ polarizer today is ready in all respects for implementation throughout the display industry. With the addition of the chemical passivation treatment and the hydrophobic polymer overcoating option, ProFlux™ polarizers can be used with confidence that they will meet all the optical and reliability design requirements.

The ProFlux™ polarizer is in production today on the pilot line at MOXTEK. This current production line processes 6" diameter glass wafers. MOXTEK is prepared to expand production in response to demand. When additional production lines are implemented, they will be sized to produce 8" diameter ProFlux™ polarizer wafers. This improvement will enable a significant price reduction. Within the next 2 years, MOXTEK expects to produce the ProFlux™ polarizer at a price which will compete favorably with current high-durability polarizer products.

As with all manufactured products, MOXTEK expects to see incremental improvements in the product. These improvements will lead to increased transmission, improved contrast, and other improvements in response to customer needs. The industry will also see several significant jumps in the available performance over the next 2 to 3 years as MOXTEK implements new technology. For example, we learned at the beginning of this paper that a smaller period wire-grid would lead to significant improvements in performance. MOXTEK expects to provide wire-grid polarizers in the not too distant future with periods approaching 100 nm. This significant advance may enable a single panel LCOS projection system in which the polarizing beam splitter is the only necessary polarization optic, by increasing the reflected and transmitted contrast. We expect that this advance will have an impact in many other areas also.

Table 2. ProFlux™ Polarizer Intellectual Property

5,986,730	Dual Mode Reflective/Transmissive Liquid Crystal Display Aparatus
6,081,376	Reflective Optical Polarizer Device with Controlled Light Distribution and Liquid Crystal Display Incorporating the Same
6,108,131	Polarizer Apparatus for Producing a Generally Polarized Beam of Light
6,122,103	Broadband Wire Grid Polarizer for the Visible Spectrum
6,208,463	Polarizer Apparatus for Producing a Generally Polarized Beam of Light
6,234,634	Image Projection System with a Polarizing Beam Splitter
6,243,199	Broad Band Wire Grid Polarizing Beam Splitter for Use in the Visible Wavelength Region
6,288,840	Imbedded Wire Grid Polarizer for the Visible Spectrum
6,348,995	Reflective optical polarizer device with controlled light distribution and liquid crystal display incorporating the same

7.0 Acknowledgements

In conclusion, MOXTEK would like to express its gratitude to the Society for Information Display for the honor of receiving the Component of the Year Silver Award. Among all the awards that MOXTEK has received for this new technology, this one stands out because it comes from those who actually use it and are thus best able to evaluate its true worth.

8.0 References

1. Schnabel, B., Kley, E., and Wyrowski, F., Study on polarizing visible light by subwavelength–period metal–stripe gratings. Opt. Eng. **38**(2) 220 – 226 (1999).