Folded optics with birefringent reflective polarizers

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ABSTRACT

Polymeric, birefringent reflective polarizers have been used to produce compact, mid-field-of-view eyepieces and wide field-of-view optics for virtual reality (VR) head-mounted displays using the “pancake” lens configuration.

Multiple configurations for pancake lens systems are discussed as are their advantages and disadvantages relative to refractive systems. Polarization control is an important consideration and the polarizing effects of different components are discussed. Designs for mid-FOV and wide FOV are presented and additional benefits of using folded optics for virtual reality systems are explored.

Keywords: folded optics, head-mounted display, reflective polarizer, catadioptric, dynamic focus

1. INTRODUCTION

Polarized catadioptric optics (i.e., pancake lenses, folded optics) were originally described by LaRussa for use in immersive flight simulators[1]. The first designs used a plane beamsplitter mirrror and a curved beamsplitter mirror; later designs replaced the curved beamsplitter with holographic mirrors[2] that were flat but produced power upon reflection.

Lacroix describes the use of a 3M reflective polarizer to improve efficiency in a polarized catadioptric eyepiece[3] where the reflective polarizer replaces the plane beamsplitter and the curved beamsplitter is used for optical power. Huxford also shows a pancake lens as a head-mounted display (HMD) eyepiece[4] and here a plane wire-grid polarizer replaces one of the beamsplitters. In both cases the use of a reflective linear polarizer minimizes the direct (not fully magnified) transmission of the display image and increases contrast. Huxford also discusses design limitations when using a plane mirror with a positive mirror such as overcorrection of field curvature and geometric distortion.

Despite the trade-offs which also include limited transmission efficiency the design freedoms available in reflective optics provide desirable benefits to designers of head-mounted display systems. These benefits include the high resolution achieved with reflective imaging, wide field-of-view (FOV), compact size, decreased weight, ability to adjust focus and the potential to form a large eye box. To realize the full potential of polarized pancake lens designs the polarized beamsplitter should be capable of provided optical power and aberration correction through control of its form.

Polymeric, birefringent reflective polarizers are interference-based optical filters that can be formed to complex shapes and integrated onto the surface of optical substrates. We will discuss the performance attributes of polymeric reflective polarizers and show specific designs enabled by the use of curved polarizers.

Finally we illustrate how polarized catadioptric systems can accommodate a wide range of refractive errors in human vision and are capable of dynamically focusing to reduce vergence-accommodation conflict in stereoscopic HMDs.

2. DESIGNS

2.1 Advantages of birefringent, polymeric reflective polarizers

The reflective polarizer in pancake lenses can be a metallic wire-grid polarizer but using polymeric, birefringent, multi-layer reflective polarizers offers numerous advantages. Multilayer optical films can be made with very low scattering and absorption that approaches the limit of thermoplastic polymers[5]. Simultaneously the polymer films exhibit high polarized reflectivity. After accounting for Fresnel reflections polarized reflectivity up to 95% across broad wavelength and at incident angles ranging from normal to +/- 60degrees[6]. This broadband and wide angle performance is important for catadioptric designs in which reflection from and/or transmission through the reflective

Digital Optical Technologies 2017, edited by Bernard C. Kress, Wolfgang Osten,
H. Paul Urbach, Proc. of SPIE Vol. 10335, 103350E · © 2017 SPIE
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2270266

polarizer may occur at high angles of incidence. Importantly, polymer reflective polarizers also exhibit low color shift across these wide angle ranges, lower than 0.002 dy and dy. With both high extinction and high transmission efficiency the visible spectrum polarization contrast of multilayer polymer polarizers can be very high.

There is another distinct benefit to using polymer polarizers in these systems. The viscoelastic nature of the constituent polymer resins allows the films to be formed to complex curvatures that include conic, asphere and even free-form geometries, and to very high curvature and high sag surfaces. Asphere forms allow for dramatic improvement in the resolution of pancake lenses. This is possible by integrating the films onto the surface of lenses with sufficient form accuracy and smoothness for imaging applications. 3M reflective polarizers integrated onto optical substrates can have sufficient form accuracy and smoothness for imaging applications.

3M has fabricated reflective polarizer lenses with spherical, asphere and freeform surfaces including "gull-wing" aspheres with curvature inflection, and integrated these lenses into catadioptric eye-pieces with wide field of view, compact form, short working distance and high resolution. Some of these designs are discussed below.

2.2 Configurations of the optical cavity

Here we describe various configurations of the reflective optical cavity. In this case the optical cavity is treated as a group independent from other elements such as lenses, windows and filters which may be a part of the complete display system.

When evaluating different configurations of polarized catadioptric systems there a large number of design trade-offs to consider. Considerations include including imaging performance, field-of-view, eye-box, image-space telecentricity, eye-relief, head-fit, manufacturability, cost, through-focus performance for accommodation of human vision and dynamic focusing, and integration of eye-tracking systems.

2.2.1 Plano-convex singlet

A simple configuration using a single, plano-convex lens is shown below. The design has a 110° FOV, 8mm eye box, 15mm eye-relief and 16mm working distance. The design can be optimized for display panel size and back working distance. The lens diameter of 54mm is less than typical inter-pupillary distance allowing for a stereoscopic display with perhaps some truncation required for head and face fit. By limiting refractive optical power and using reflective optical power the wide-field resolution of these designs can exceed what is possible with refractive lenses of similar focal length.

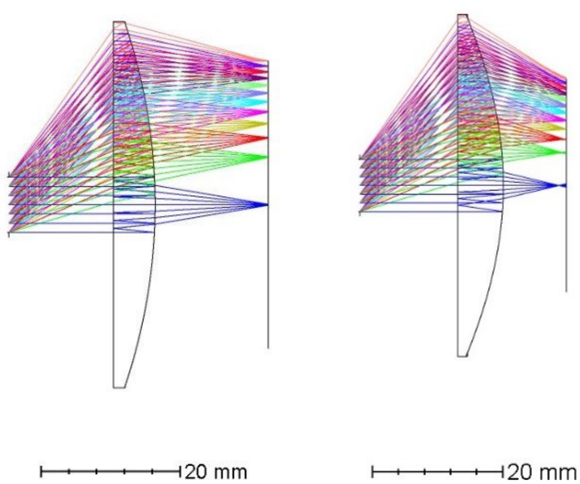


Figure 1. High and low curvature singlet designs with different working distance and image size

A thin lens with low curvature provides for high resolution across wide fields, low weight, minimal Petzval field curvature, and large working distance but also has a large total track length from display to cornea compared to more complex catadioptric designs. Large working distances may be necessary to provide room for additional components such as a tilted near-infrared mirror for the integration of an eye-tracking system.

The lens is also designed to be injection molded with minimum birefringence which is important for maintaining a high degree of polarization through multiple passes in the folded path. The system is also close to being image-space telecentric which provides a few benefits. Telecentric or nearly telecentric systems will have maximum brightness and efficiency for most displays in which peak brightness occurs on-axis. They will also have a limited change magnification if focus is adjusted to accommodate refractive errors in the wearer's eyes.

Increasing the curvature of the singlet design reduces focal length, working distance and total track length. The degree of telecentricity decreases as does resolution, while Petzval field curvature increases. Field curvature may require the user to change focus at different eye gaze angles but may be acceptable in some systems.

Overall benefits of this configuration include relatively simple lens geometry, the use of a planar reflective polarizer and lower cost fabrication. Downsides include limited resolution, a limit to field-of-view and a trade-off between eye-relief and lens diameter. Increasing eye-relief requires an increase in lens diameter and this can impact head fit and whether a single display panel can be utilized or if two, tilted panels can be used that are wrapped slightly around the head towards the temples.

2.2.2 Cemented doublet design

In this design the beamsplitter lens and the reflective polarizer lens can be fabricated independently, and a quarter-wave retarder can be integrated into the bond line during assembly. Allowing for a curved reflective polarizer enables a more compact form by decreasing working distance and allowing for a smaller aperture on the eye side of the magnifier. Using conic and asphere forms for the reflective polarizer enables higher resolution and reduced aberrations when compared to the plano-convex singlet.

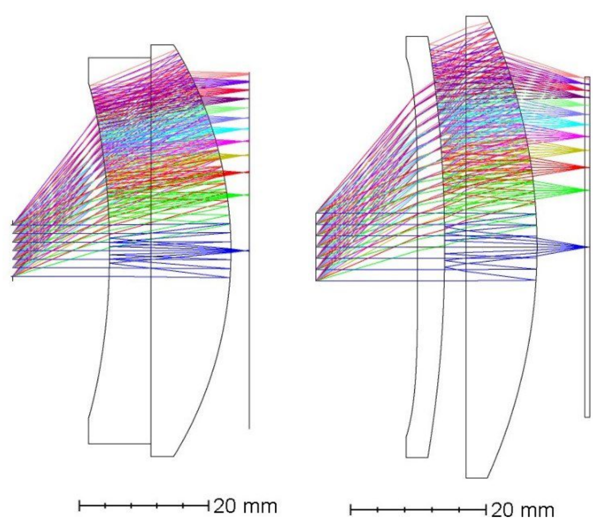


Figure 2. Cemented and air-spaced doublet designs with equal field of view and similar image sizes.

2.2.3 Air-spaced doublet

By providing an air space between the beamsplitter lens and the reflective polarizer lens two additional refractive surfaces are provided which can be used to balance aberrations in the optical system. Shown above is a 110deg FOV design that achieves high resolution by utilizing aspheres on both surfaces of the reflective polarizer lens, and a spherical plano-convex lens for the beamsplitter. Compared to the cemented doublet the air-space doublet can be lighter in weight and allows for adjustment of lens position which can create focus accommodation. Trade-offs include higher Fresnel losses and the need for additional anti-reflection coatings.

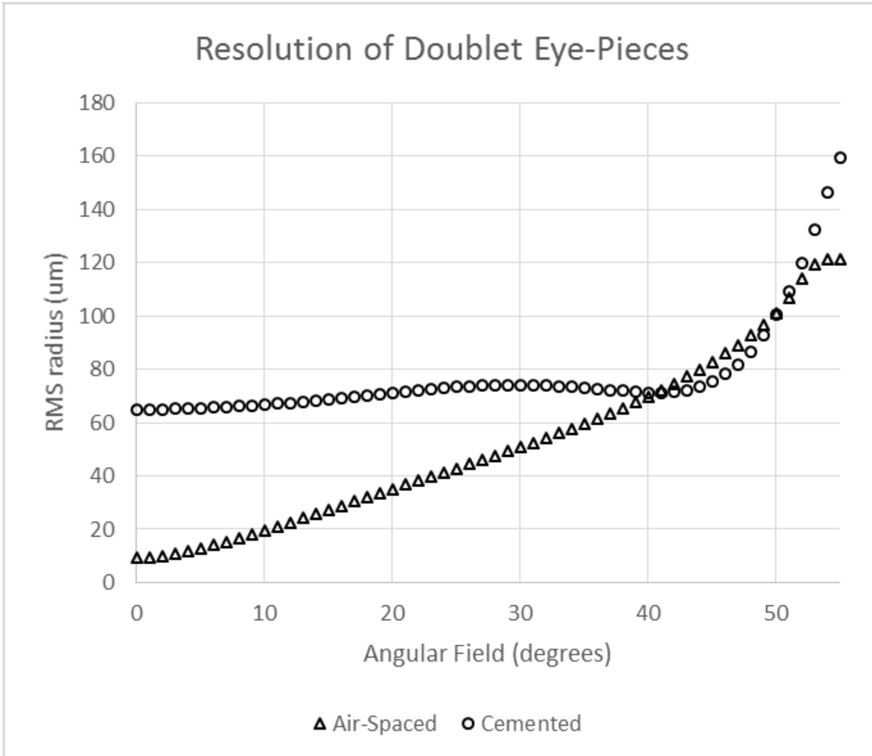


Figure 3. Polychromatic RMS radius spot size of the two 110deg FOV doublet designs (486nm, 588nm and 656nm)

2.2.4 First surface versus second surface mirrors

In the case of an air-spaced doublet it may be useful for one or both of the reflectors to be first-surface mirrors. An advantage of using first-surface mirrors is that birefringence in either or both of the lenses has a minimized effect. When second surface mirrors are used birefringence in the substrates or lenses has a cumulative effect in each of the three transmissions through the optical materials. However, using first surface mirrors can also limit eye-relief or have other practical impacts on the system design. For this reason considerations of manufacturing options and system performance must be made.

3. VARIABLE FOCUS CATADIOPTRIC SYSTEMS

Catadioptric systems have a unique advantage when focusing is required. Because of the triple pass through the optical cavity small changes in the location of one or both of the reflective surfaces can have a large effect on focus. In head-mounted display eye-pieces focus range is very desirable. In a basic implementation focus can be used to correct for refractive errors in the human eye (i.e. myopia and hyperopia) and this can be extended to astigmatism correction[7]. In a more elaborate form focus can be deployed to create displays that dynamically focus based on gaze direction. Fixed focus is a well-known limitation to many stereoscopic display designs; vergence-accommodation conflict can results in eye-strain and headaches. Vergence-accommodation conflict can be minimized by tracking the gaze point of the eye(s) with an eye-tracking system and re-focusing the eye-piece to the correct virtual image distance, the depth of the object of the subject's gaze.

3.1 Focus Speed

In such a system the focus time should match or exceed the accommodation velocity for the eye. Focus time includes gaze detection, focus distance determination, lens acceleration, lens movement, lens deceleration and lens stop. Accommodation time includes any latency in response. Typical accommodative velocities for 1.0D near-far and far-near vergence stimuli changes are approximately 2 diopters per second[8].

By using thin, low-inertia lenses in polarized catadioptric systems this focus can be achieved very rapidly. Sufficient torque or force is available through a variety of means: stepper motors, ultra-sound (i.e. wave motors), piezo-motors, squiggle motors and other types of actuators.

3.2 Example variable focus design

As an example a 70-degree FOV polarized catadioptric system is shown below in figure 4. The design has 17mm of eye relief and a 32mm total track length. A lens position plot is shown for a focus range from -8 diopters to +8 diopters. This system is able to present the virtual image between infinity and a 25cm near point for users that have vision ranging from +8D hyperopia to -4D myopia. Figure 5 shows the lens position profile for the entire focus range.

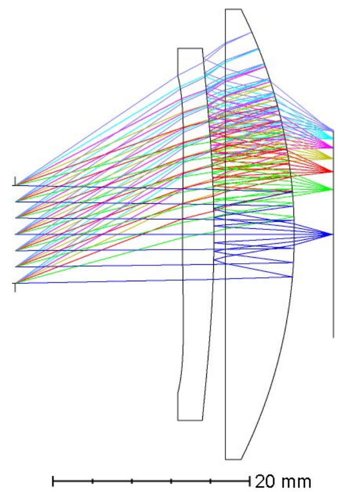


Figure 4. A 70deg FOV design using a thin, plastic aspheric reflective polarizer lens and a spherical, glass plano-convex beamsplitter lens. The beamsplitter lens is adjusted 1.05mm away from the display to create -4D accommodative power for a myopic eye.

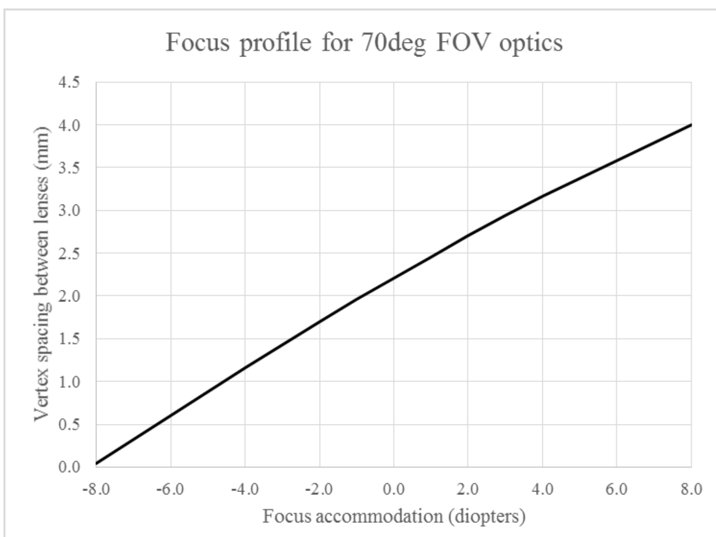


Figure 5. Lens position and focus profile for the 70deg FOV design

3M has designed an assembled a prototype of this dynamically focusing HMD which is shown in figure 6. The system uses a stepper motor to actuate the plano-convex beamsplitter lens while keeping the asphere reflective polarizer lens fixed. A flat hot mirror is used off-axis to both illuminate and view the eye to determine gaze direction. An 850nm LED and Raspberry Pi camera with no-infrared filter is used in the eye tracking system with an absorbing visible light filter covering the camera. An LG Nexus 5x mobile phone is used for the display; a Raspberry Pi is used for the eye-tracking software and to send signals to the motor controller. Photos taken of two displays as viewed through the optics are shown in figures 7a, 7b, 8a and 8b below.

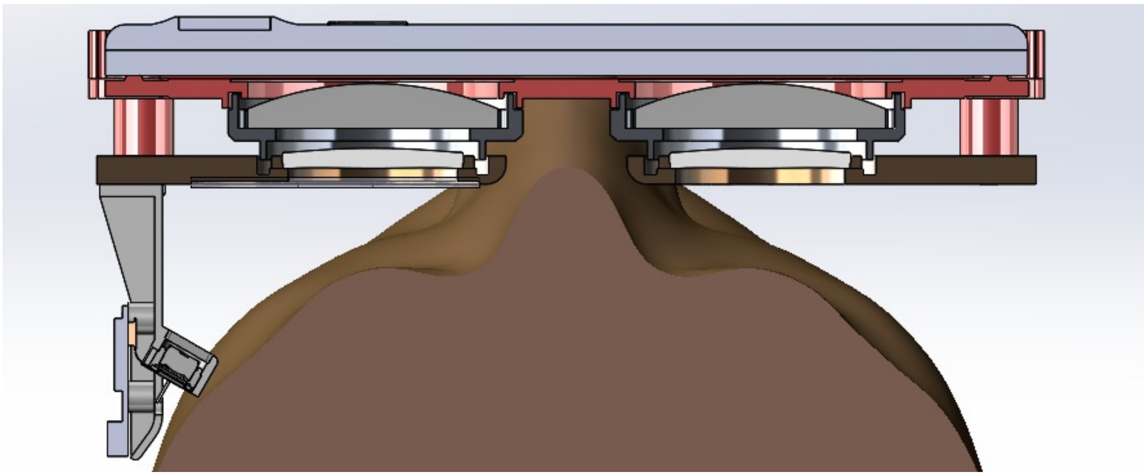
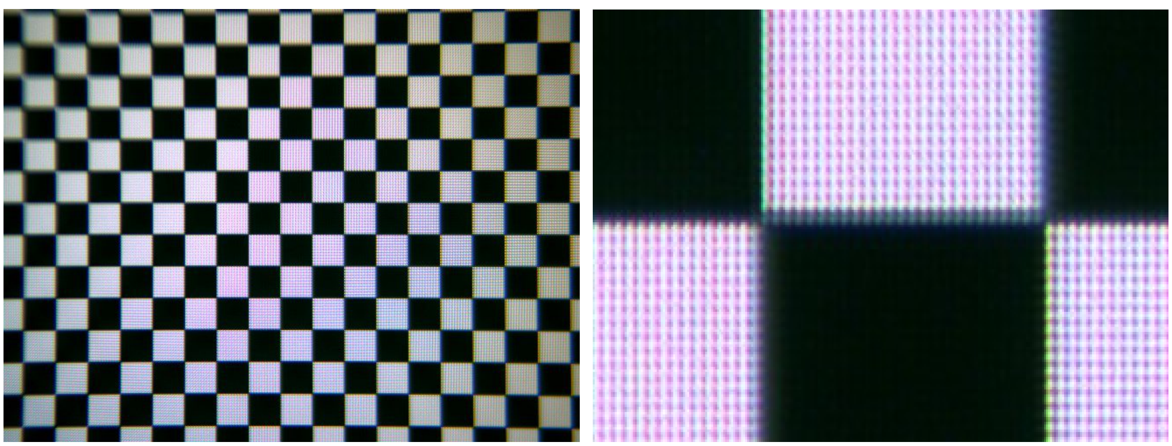


Figure 6. Top view schematic of dynamically focusing system. Eye-tracking camera and LED source are at left temple. A hot mirror plate is in front of the left-eye lens.



Figured 7a and 7b. Photograph of a microdisplay through variable focus optics. Image 8a (left) spans approximately 0.25” and 18° horizontally. Image 8B (right) spans approximately 0.03” and 2° horizontally. The display is manufactured by Kopin Corporation and is a 0.97” SXGA transmissive LCoS microdisplay with 15um pixel pitch.

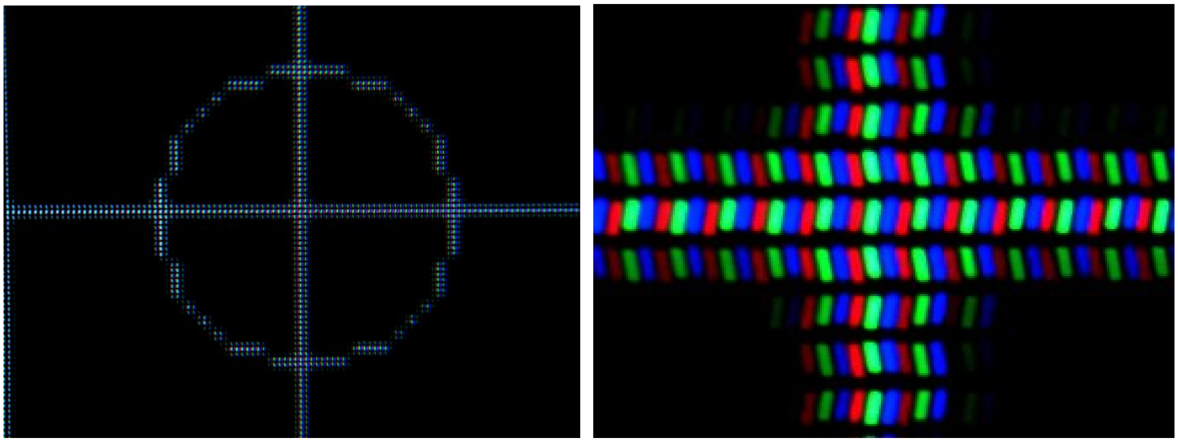


Figure 8a and 8b. Photograph of a mobile phone display through variable focus optics. Image 9a (left) spans approximately 0.25” and 18° horizontally. Image 9b (right) spans approximately 0.03” and 2° horizontally. The display is part of a LG Nexus 5x mobile phone.

4. SUMMARY

Polarized catadioptric systems have unique advantages when used as eye-piece magnifiers for head-mounted displays. Using polymeric reflective polarizers allows for even more design freedom and higher system performance by increasing field-of-view, decreasing working distance and enabling higher resolution at wide fields. Systems have been proposed that balance high performance and compact size with manufacturability and cost considerations. The ability to statically or dynamically vary focus should enable wider adoption of head-mounted displays by reducing visual discomfort, and eliminate the need to wear eyeglasses while using HMDs.

5. ACKNOWLEDGEMENTS

Andrew Ouderkirk inspired the initial efforts to build polarized folded optics using 3M reflective polarizing films. Gregg Ambur helped developed a robust process for integrating films onto the surfaces of lenses. Ben Sonnek and Robert Jennings developed techniques for forming polymer interference films to high curvatures. Zhisheng Yun designed catadioptric systems that balance optical performance with practical considerations towards manufacturability and scale. Kayla McGrath, Jo Etter and Tom Corrigan devised elegant designs for the fixtures and tools used to fabricate and assemble these systems. Glen Kappel and Chris Youngers designed the dynamically focusing headset and Milo Oien-Rochat developed the eye-tracking software. Erin McDowell has driven our team to imagine designs that will inspire our customers and Sue Kent has helped us create them.

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