In optical see-through head-mounted displays, it has been a common challenge that the displayed image lacks brightness and contrast compared with the direct view of a real-world scene. Consequently, such displays are usually used in dimmed lighting conditions, which limits the feasibility of applying such information displays outdoors or in scenarios where well-lit environments, such as in operation rooms, are required. The lack of image brightness is aggravated in the design of a see-through head-mounted projection display (HMPD). For instance, the overall flux transfer efficiency of existing HMPD designs is less than 10%. The design of a polarized head-mounted projection display (p-HMPD) is presented. The images of a p-HMPD system can potentially be three times brighter than those in existing HMPD designs. It is further demonstrated that the p-HMPD design is able to dramatically improve image brightness, contrast, and color vividness with experimental results. Finally, the design of a compact optical system and helmet prototype is described. © 2007 Optical Society of America

1. Introduction

Mixed- and augmented-reality (MR–AR) technology is a paradigm where computer-generated digital information is selectively superimposed upon a real-world scene to supplement a user’s sensory perception of the physical environment. It has been explored for a wide range of applications for 3D scientific visualization, medical training, and engineering processes. One of the key enabling technologies in MR–AR systems is a 3D display that is able to seamlessly combine virtual and real information, which is called creating see-through capability.

Optical see-through head-mounted displays (OST-HMDs) have been one of the basic approaches to combining computer-generated virtual objects with the views of real-world scenes required for MR–AR systems. In an OST-HMD, the direct view of the physical world is maintained, and computer-generated virtual images are optically superimposed onto the real scene via an optical combiner. This optical approach allows a user to see the real world in full resolution and introduces less intrusion into the view of the real world than video see-through displays where real-world views are captured through video cameras. Therefore an OST-HMD system is preferred for tasks where eye–hand coordination or a non-blocked real-world view is critical.

Designing a wide field-of-view (FOV), compact, and nonintrusive OST-HMD, however, has been a challenge. A head-mounted projection display (HMPD), pioneered by Fisher and Fergason, deviates from the conventional approaches to HMD designs. A schematic of a monocular HMPD configuration is illustrated in Fig. 1. Two major aspects distinguish the HMPD technology from conventional HMDs and projection systems: Projection optics replaces an eyepiece- or microscope-type lens system in a conventional HMD design, and a retroreflective screen substitutes for a typical diffusing screen in a conventional projection system. The projected light is thus directly retroreflected back to the exit pupil of the projection system where the eye is positioned to view the projected image. The unique combination of projection and retro-reflection not only enables stereoscopic capability but also provides intrinsically correct occlusion of computer-generated objects by real ones and offers the capability of designing wide FOV, low-distortion optical see-through displays. More detailed discussions on the pros and cons of the HMPD technology can be found in Hua et al. Recent technology ad-
Enhancements and applications will be reviewed in Section 2.

Besides the challenge of designing wide FOV, low-distortion optics, the images of optical see-through displays are commonly lack of brightness and contrast compared with the direct view of a real-world scene. While the luminance level of an immersive HMD is usually required to be equal to or greater than approximately 17 cd/m² for optimal visual acuity,9 the image brightness of an OST-HMD must match the average luminance level of its working environments. The average luminance of outdoor scenes is typically approximately 5000 to 6000 cd/m², and a well-lit indoor environment approximately averages 400–500 cd/m². The state-of-the-art microdisplays suitable for HMDs, however, yield on average 100 cd/m² of luminance for backlit active-matrix liquid-crystal displays (AMLCD), 300 to 1000 cd/m² for liquid crystal on silicon (LCOS) displays, and 50 to 600 cd/m² for organic light-emitting displays (OLED).

The problem of low image brightness and contrast is worsened due to the light attenuation through an optical combiner interface required in see-through displays, resulting in low luminance transfer efficiency of the optical system. In conventional OST-HMDs, using a 50/50 beam splitter will attenuate the light, from both a displayed image and the real scene, by 50%. Consequently, such displays are usually used in dimmed indoor environments, which limits the feasibility of applying such information displays outdoor or in scenarios where well-lit environments such as in an operation room are necessary.

The low-efficiency problem is aggravated in a see-through HMPD in which the projected light is split twice through a beam splitter as illustrated in Fig. 1. Using a 50/50 beam splitter leads to the loss of at least 75% of the light from a displayed image and 50% of the light from the real scene. The light from the displayed image is further attenuated by as high as 80% through an imperfect retroreflective screen.10 The actual luminance returned back to the exit pupil is approximately 4%–10% or less of the display luminance. For instance, providing the usage of AMLCDs, the observed peak luminance is approximately 4 to 10 cd/m² or lower, which imposes significant restrictions on the lighting conditions of working environments and limits applications demanding well-lit environments. Fergason suggested a conceptual improvement to the technology by adding a secondary retroreflective material located at 90° from the primary retroreflective surface.7 This approach can increase the luminous efficiency of the display, but it compromises a significant property of the original HMPD concept, that is, the capability of natural occlusion of virtual objects by real objects placed between the user and the retroreflective screen.

In this paper we present the design of a polarized head-mounted projection display (p-HMPD) to address the image brightness challenge.11 The new design scheme significantly improves the luminance efficiency of the display by applying polarization techniques. The observed image through the polarized system can potentially be three times brighter than existing nonpolarizing HMPD designs. The rest of the paper is organized as follows. In Section 2 recent advancements in HMPD research and application are reviewed. The conceptual design of a p-HMPD design is described in Section 3. The optical design for a compact prototype is described in Section 4, the design of a compact helmet system is described in Section 5, and the experimental results are presented in Section 6.

2. Related Work

The system described by Fisher was a biocular configuration with one microdisplay, and the same image was viewed by both eyes.6 Fergason extended the biocular concept to binocular displays.7 Since these pioneering efforts, the HMPD concept has been recently explored extensively by several groups of researchers, and the technology has evolved significantly.8,10–22

In the early work, head-mounted prototypes implemented from off-the-shelf components were demonstrated by Kijima and Ojika12 and by Parsons and Rolland13 for medical visualization. Shortly after, Tachi et al.14 and his group demonstrated a non-head-mounted configuration that utilized two video projectors together with a retroreflective screen. They further extended this configuration to a head-mounted system.15

Custom-designed optics for HMPDs and a study of retroreflective material properties were initially explored by Poizat and Rolland.16 Later, Hua and Rolland investigated the engineering challenges in developing a fully custom-designed HMPD system and studied the imaging properties of retroreflective materials and their effects on image quality.8,10

Fig. 1. (Color online) Schematic of a monocular head-mounted projection display.
They made further efforts to design wide FOV, low-distortion, and lightweight miniature optics for HMPD systems, using advanced optical design technology such as diffractive optical elements, aspheric surfaces, and plastic materials.\textsuperscript{13} The optics for each eye weighs only 6 g with a 52° FOV and less than 2.5% distortion. These efforts have led to the success of custom-designed compact prototypes.\textsuperscript{18}

Several efforts were made thereafter to explore more compact or wider FOV display designs. For instance, Ha \textit{et al.} designed a 70° wide FOV projection lens,\textsuperscript{18} and Rolland \textit{et al.}\textsuperscript{20} developed an OLED-based 42° prototype and a teleportal HMPD system. Martins \textit{et al.} explored a design that integrated a retroreflective screen within the helmet for an outdoor environment,\textsuperscript{21} and Curatu \textit{et al.} reported the design of a HMPD integrated with eye-tracking capability.\textsuperscript{22}

A wide range of single-user applications, such as object-oriented and visual-haptic displays,\textsuperscript{14,15} distributed display environments,\textsuperscript{23} medical visualization,\textsuperscript{13} and optical camouflage,\textsuperscript{24} have been explored and demonstrated using the HMPD concept. The HMPD technology has also been explored in multiuser collaborative environments. For instance, Rolland \textit{et al.}\textsuperscript{20} and Davis \textit{et al.}\textsuperscript{25} have demonstrated a deployable room display environment for medical training. By exploring several unique properties inherent in HMPD technology, Hua \textit{et al.} have developed a multiscale collaborative infrastructure, referred to as SCAPE, to support versatile modes of user interaction and collaborative operation in augmented virtual environments.\textsuperscript{26–29}

3. Conceptual Design of a Polarized HMPD

A. Illumination Challenge

As briefly discussed in Section 1, existing HMPD designs confront the challenge of low image brightness and contrast. Consider a pixel on the microdisplay. Let us denote the viewing angle subtended by the chief ray of the given pixel in the eye space as $\theta$, which characterizes the FOV of an HMPD system. The luminous flux of the pixel collected by the exit pupil of a HMPD system can be modeled by

$$\Phi_i(\theta) = r_{\text{B-trans}}(\theta)r_{\text{retro}}(\theta)r_{\text{B-refl}}(\theta)\alpha_{\text{eff}}(\theta)\Phi_i(\theta),$$

where $\Phi_i$ is the luminous flux collected by the projection system from the given pixel on the microdisplay, $\alpha_{\text{eff}}$ is the transmittance of the projection system, $r_{\text{B-refl}}$ and $r_{\text{B-trans}}$ are the reflectance and transmittance of the beam splitter, respectively, and $r_{\text{retro}}$ is the retroreflectance of the retroreflective screen. $r_{\text{B-refl}}$, $r_{\text{B-trans}}$, and $r_{\text{retro}}$ depend on the viewing angle or the incidence angle upon the associated optical surfaces.

The transmittance of a well-designed projection system can typically be approximately 80% or higher. However, a theoretical 50/50 beam splitter will lead to a 75% loss of the light owing to the dual pass through the beam splitter (Fig. 1), without taking into account the factors of absorption and reflection loss. A further light loss, varying from 50% to 80%, is observed from the currently available retroreflective materials.\textsuperscript{9} Therefore the accumulative light efficiency in existing HMPD designs is approximately 4%–10%. The variation depends mainly on the retroreflectance of the screen. The low efficiencies of the beam splitter and the retroreflective screen account for the major luminance attenuation. Minimizing the loss from the beam splitter is critical for improving the efficiency of luminance transfer in a HMPD system.

B. Polarized HMPD

To address the image brightness challenge described above, we present a simple but elegant design of a p-HMPD.\textsuperscript{11} The main departure from a conventional HMPD design is that the polarization states of the display system are manipulated to maximize the efficiency of reflection and transmission. A schematic of a monocular p-HMPD configuration is shown in Fig. 2. One of the modifications is to replace a nonpolarizing beam splitter in Fig. 1 with a polarizing beam splitter (PBS). To gain maximum reflection and minimize the transmission loss of light incident upon the PBS from the projection optics, we further ensure that the projected light is linearly polarized, and its polarization direction is matched with the high-reflection polarization of the PBS, which is usually referred to as the S polarization.

The microdisplays used in HMD designs are usually liquid-crystal (LC) flat panels, and thus the light emergent from these microdisplays is often linearly polarized. In most of the LC-based microdisplays, the polarization direction is usually parallel with the width or height side of the panel. Simply aligning the polarization direction of the panel with the S-polarization axis of the PBS can ensure high reflec-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{(Color online) Schematic of a monocular polarized head-mounted projection display.}
\end{figure}
tion of light. In HMD systems, however, it is usually desirable to align the width of the panel with the horizontal FOV for a preferred aspect ratio of the visual field. Therefore when the polarization axis of the microdisplay is perpendicular to the S polarization of the PBS, a half-wave plate retarder can be inserted in front of the PBS, with its fast axis oriented at a 45° angle with the S polarization, to rotate the polarization axis of the projected light by 90°. In microdisplays where their polarization direction is at an arbitrary angle with the S polarization of the PBS, a polarization rotator can be carefully designed to rotate the polarization axis of the projected light accordingly. Except for a low-percentage absorption loss through a retarder or polarization rotator, the requirement for a linearly polarized projected light usually does not lead to significant loss of light using LC-based microdisplays. Owing to the high reflectance of a PBS for the S-polarization light, the projected light is reflected with very high efficiency (e.g., approximately 93% for the wire-grid PBS we used in Subsection 4.C), opposed to approximately 50% or more loss through a non-PBS interface.

After the projected light is reflected by the PBS, it is retroreflected back to the same PBS by a retroreflective screen. The potential depolarization effects by the retroreflective screen were recently tested with an Aximuthic polarimeter. Results show that depolarization is less than 10% for incidence angles within ±20° and is less than 20% for angles up to ±30°. The test further showed that the retroreflected light remains dominantly the same type of polarization as its incidence light. For instance, when the incident light is S polarized, the retroreflected light remains S polarized, parallel to the high-transmission polarization of the PBS. The depolarization artifacts will cause a decrease of luminance transfer efficiency varying with incidence angles. Such angular dependence of luminous efficiency visually creates vignettinglike artifacts and reduces image uniformity.

To minimize transmission loss, it is required to match the polarization axis of the retroreflected light with the P-polarization axis of the PBS. As shown in Fig. 2, a quarter-wave retarder is inserted between the PBS and the retroreflective screen, with its fast axis at a 45° angle with the polarization direction of the light emergent from the PBS. With this modification, the projected light is manipulated through a consecutive sequence of polarization states, from its initial state of S polarization to right circular polarization (RCP) by the first pass of the quarter-wave retarder, from RCP to left circular polarization (LCP) at the interface of the retroreflective screen, and from LCP to P polarization after the second pass of the retarder.

Because of the high transmittance of P-polarization light by a PBS (e.g., approximately 87% for the wire-grid PBS in Subsection 4.C), the retroreflected light is transmitted efficiently and is collected at the exit pupil, opposed to approximately 50% of transmission loss through a non-PBS interface. With the above modifications, Eq. (1) for a p-HMPD can be rewritten as

\[ \Phi_L(\theta) = \alpha_{wp}^2(\theta) r_{P\text{-trans}}(\theta) r_{C\text{-retro}}(\theta) r_{S\text{-retro}}(\theta) \alpha_{eff}(\theta) \Phi_I(\theta), \]

where \( \alpha_{wp} \) is the transmittance of the wave-plate retarder, \( r_{S\text{-retro}} \) and \( r_{P\text{-trans}} \) are the reflection and transmission efficiencies of the PBS for S and P polarizations, respectively, and \( r_{C\text{-retro}} \) is the retroreflectance of the retroreflective screen for circularly polarized light. The luminance transfer efficiency in a p-HMPD can be up to four times the efficiency in nonpolarizing HMPD designs using a theoretical 50/50 beam-splitting method. Practically, we expect the observed image luminance to be approximately 15%–40% of the microdisplay luminance. In addition to FOV and wavelength dependence, the efficiency variation depends mainly on the retroreflectance of screen choices.

4. Design of a Compact Optical System

Based on the schematic design described in Section 3, a monocular prototype was designed and built on an optical bench from off-the-shelf optics to validate the improvement on imaging quality. Further efforts were made recently to design a compact, low-cost optical system and to develop a head-mounted prototype.

A. System Specifications

A pair of existing 1.3 in. (1 in. = 2.54 cm) backlit colorAMLCDs, with a resolution of (640 × 3) × 480 pixels and a 42 μm pixel size, was selected as the miniature displays. The display, tested with a polarization analyzer, is linearly polarized, and its polarization axis is aligned with the width of the panel.

We target for a display with a diagonal full FOV between 50° and 60°, which corresponds to 35.3–28.6 mm of focal length for the projection lens. The targeted FOV stems from several considerations and trade-offs. First, our previous investigation on retroreflective materials shows that the retroreflectance of currently available materials drops off significantly for light incident at angles beyond ±35°. A FOV beyond 70° will inevitably cause vignettinglike artifacts and compromise image uniformity. Second, increasing the FOV will degrade the angular resolution of the display. The given miniature display allows only a narrow (i.e., 13°) FOV to meet the requirement for 1 arc min visual acuity at the fovea, while a 60° diagonal FOV offers a balanced angular resolution of 4.5 arc min per pixel. Finally, a wide FOV requires beam splitters and retarders with large dimensions, which consequently compromises the compactness and light weight of the display system.

Several high-quality projection optics have been designed for HMPDs, using the combination of diffractive optical elements, aspheric surfaces, and plastic materials. The fabrication costs of these lenses, however, are intimidating. Rather than designing such a costly system, we aim to design compact projection optics composed of 3–4 glass elements.
with low-cost spherical surfaces. The system, together with the polarizing components, should be optimized to minimize all primary aberrations and particularly achieve low distortion and chromatic aberrations. The back focal length of the projection lens is required to be at least 25 mm owing to the packaging considerations of the helmet design discussed in Section 5.

The targeted diameter of the exit pupil in the projection system is 10–12 mm, which leads to a projection system with a f/# of 2.5–3.5. The large pupil size allows a swivel of approximately ±21 up to 26.5° within the eye sockets without causing vignetting or loss of image with a typical 3 mm eye pupil in the lighting conditions provided by HMPDs. Furthermore, it tolerates approximately 7 to 9 mm differences of the interpupillary distances (IPD) among different users without the need to mechanically adjust the IPD of the binocular optics.

In the design of a head-mounted prototype, an effective eye clearance of 23 mm is necessary to accommodate users wearing eyeglasses. Though it is less challenging to achieve large eye clearance in HMPD designs than in eyepiece-based HMDs, it can be problematic when the FOV is large. In a HMPD design, the exit pupil of the system is the mirror image of the entrance pupil of the projection optics. On one hand, if the separation between the entrance pupil of the projection optics and the beam splitter is not sufficient, the reflected light by the beam splitter at large field angles may be blocked by the projection optics. On the other hand, the required dimensions of the beam splitters and the retarders scale with the FOV and the eye clearance distance. To ensure compactness, the entrance pupil distance of the projection optics is optimized to be approximately 5–10 mm inside the lens. The specification of the system is summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microdisplay Type</td>
<td>Active Matrix LCD, backlighting</td>
</tr>
<tr>
<td>Active display area</td>
<td>26.4 mm (width) × 19.8 mm (height), 33 mm (diagonal)</td>
</tr>
<tr>
<td>Pixel resolution</td>
<td>(640 × 3) × 480 pixels</td>
</tr>
<tr>
<td>Pixel size</td>
<td>~42 μm, square</td>
</tr>
<tr>
<td>Projection optics</td>
<td>Effective focal length</td>
</tr>
<tr>
<td>Entrance pupil diameter</td>
<td>10–12 mm</td>
</tr>
<tr>
<td>Entrance pupil distance</td>
<td>5–10 mm</td>
</tr>
<tr>
<td>Back focal length</td>
<td>&gt;24 mm</td>
</tr>
<tr>
<td>Total number of optical elements</td>
<td>3–4</td>
</tr>
<tr>
<td>PBS</td>
<td>Size</td>
</tr>
<tr>
<td>S-polarization reflection</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>P-polarization transmission</td>
<td>&gt;85%</td>
</tr>
<tr>
<td>Retarder</td>
<td>Retardance</td>
</tr>
<tr>
<td>Size</td>
<td>Quarter-wave (broadband)</td>
</tr>
<tr>
<td>Wavelength</td>
<td>Visible</td>
</tr>
<tr>
<td>FOV</td>
<td>50°–60° (diagonal)</td>
</tr>
<tr>
<td>Distortion</td>
<td>&lt;5% over the entire FOV</td>
</tr>
<tr>
<td>Modulation transfer function (MTF)</td>
<td>&gt;30% @ 12.5 lps/mm (given by the pixel size of the microdisplay)</td>
</tr>
<tr>
<td>Spot size (rms)</td>
<td>&lt;42 μm</td>
</tr>
<tr>
<td>Eye clearance</td>
<td>20–25 mm</td>
</tr>
</tbody>
</table>

B. Design of Projection Optics

After initial trials of optimization starting from several patent lenses, we selected U.S. patent lens 2799207 as a starting point. It is a five-element f/2.0 system with a full FOV of 70°, which offered us the flexibility to explore a range of FOV and f/# combinations. We initially scaled the lens to a range of focal lengths between 25 and 35 mm, and roughly optimized the scaled lenses to meet the first-order requirements specified in Table 1. For each of these lenses, we then explored the main considerations of packaging and helmet design factors discussed in Section 5. This exercise allowed us to specify valid constraints for the design of a projection lens in the context of helmet design and to visualize how the subsequent helmet design would be affected. Finally, we decided to aim for a f/3.2 projection system with 56° FOV, which offers a good balance between display quality and helmet compactness. The projection lens has a 31.5 mm focal length and a 10 mm entrance pupil.

The initial five-element system was then optimized with CODE V by Optical Research Associates. During the initial steps of optimization, all the curvatures of the refractive surfaces and the thickness between the surfaces were set as variables. The surface materials were also set as variables; however, they were constrained to eliminate high-refraction-index materials. Five visual fields, 0, 0.28, 0.55, 0.76, and 1 (i.e., on axis, 8°, 16°, 22°, and 28°, respectively) were optimized. The weights for the five fields were adjusted accordingly during the optimization process. A few iterations led to an optimized five-element system shown in Fig. 3(a) offering a circular FOV of 58° for a full unvignetted 10 mm pupil. The optimized system demonstrates 30% of modulation contrast at a spatial frequency of 40 lps/mm. It offers a spot size of less than 1/4 of the pixel size for the on-axis field and approximately 1/2 of the pixel size for the maximum field. Both the modulation transfer function (MTF) and spot size performances are significantly better than the minimal requirements listed in Table 1. Overall aberrations are well corrected and balanced. However, the system has approximately 13% distortion and a fairly large field curvature, which is not desirable in display designs. The overall length of the optics itself is approximately 42 mm, with a back focal length of 41 mm. The diameter of the largest lens element is over 35 mm.
Further optimization was performed to balance between performance and compactness. The cemented doublet in Fig. 3(a) was replaced by a biconcave negative singlet with the same equivalent optical power. Several iterations of optimization led to a four-element starting point, from which a global optimization process was performed. During the global optimization process, the major constraints were the effective focal length, overall length, as well as general constraints on the minimum and maximum thickness of the elements.

Among the many potential solutions synthesized through the global optimization process, the format shown in Fig. 3(b) was selected for further optimization, mainly because of the combination of its elegant lens shapes, compactness, and relatively low value of error function. Further optimization was performed progressively by adjusting the weights to the five visual fields to achieve approximately the same MTF performance across the FOV, in addition to the constraints on the overall length of the lens assembly and the back focal distance. We further constrained the glass map so that high-refraction-index materials could be avoided. After reaching a well-balanced optical performance and compactness, the fictitious materials were replaced with closely matched low-cost glasses.

During the final stage of optimization, a constraint was added to ensure the back focal length to be at least 25 mm and limit the third-order distortion, which was less corrected than other third-order aberrations. After a few iterations, the system distortion was reduced to 3.8% at the 28° field. The layout of the final design, with a total weight of 6 g, is shown in Fig. 3(c). It is worth noting that the telecentric requirement was relaxed in the design to gain compactness. In the display space, the chief ray angle of the 1.0 field is approximately 32°. Such a steep incident angle at the marginal field can potentially reduce image uniformity for LC-based displays, yielding vignetting-like artifacts and compromising the image contrast of the peripheral field. However, enforcing telecentric constraint requires that the lens aperture be at least the same size as the microdisplay source, which significantly compromises the compactness of a HMD design. The AMLCD microdisplays used in this design offer considerably large viewing angles. The luminance and contrast attenuation within ±30° of viewing angles appears to be acceptable. In desktop displays 20% nonuniformity across the entire visual field is not unusual.

The spot diagrams across the five fields are shown in Fig. 4(a). The rms spot diameter is smaller than the pixel size of the LCD display across the entire visual field. The rayfan plots and field curves are shown in Figs. 4(b) and 4(c), respectively. The residual astigmatism reaches a maximum of 0.25 mm at the 21° FOV, and there is some residual coma at the 28° field. The distortion of the system is well corrected and less than 3.8% across the overall FOV. The polychromatic MTF for the full 10 mm pupil across the five representative field angles is shown in Fig 4(d). The modulation contrast of the design across the entire visual field is approximately 30% at a spatial frequency of 20 cycles/mm and over 50% at 12.5 cycles/mm, which is the spatial frequency of the targeted LCDs (in Table 1). Therefore the optics performance slightly exceeds the requirements by the microdisplays.

The performance of the design in Fig. 3(c) can hardly be improved without making significant changes to the surfaces. We experimented adding an aspheric surface to the first surface of the second element. It turned out to be very useful to correct the residual aberrations. However, the design with-
out aspherics met the requirements, and we decided to leave the option of an aspheric surface out.

C. Polarizing Components

One of the key requirements for the polarizing components (i.e., PBS and retarders) are their spectral responses to visible wavelengths to minimize the wavelength dependence of luminous efficiency, which results in color temperature displacements of the display system. It is also required that the PBS and the retarder have a wide acceptance angle to match the FOV of the projection optics. Finally, the form factor and weight of these components are greatly concerned for the consideration of display compactness and portability.

Our initial experiments showed that the widely used PBS cubes are inadequate for the proposed system. While PBS cubes usually have high reflection and transmission ratios (e.g., as high as 99%) and high extinction ratios (e.g., 1000:1), their acceptance angle is usually very narrow owing to the limited range of the Brewster window. A cube PBS with a larger acceptance angle might be designed at the cost of using high-refractive-index prisms and poor reflection-transmission uniformity across the angular aperture. Furthermore, given the wide FOV of the projection optics, the required aperture for the PBS is larger than 70 mm. The form factor and the unneglectable weight of two cemented prisms at such a large dimension inevitably challenge the design of a light and compact helmet.

Alternatively, a 65 mm × 45 mm nanometer-scale wire-grid plate PBS was custom designed, with a plate thickness of 1.6 mm. The wire direction of the PBS is aligned with the width of the plate to match with the polarization axis of the microdisplay for maximum efficiency. The wire-grid PBS offers many advantages such as wide acceptance angles, low light absorption, light weight and plate form, broadband, and potential low cost owing to integrated-circuit-type fabrication processes. The wire-grid coating can be thought to function as a dielectric interface for the P polarization but as a metal surface for the S polarization. Consequently, a wire-grid PBS usually

Fig. 4. (Color online) Performance analysis of the design in Fig. 3(c) for a 10 mm unvignetted pupil. (a) Spot diagram across five field angles; (b) rayfan plots; (c) plots for spherical aberration, astigmatism, and distortion; (d) polychromatic MTF as a function of the spatial frequency in line pairs per millimeter (cyles/mm).
has a high contrast ratio for $S$ polarization and a lower contrast for $P$ polarization.

After comparing the various retarder techniques, a 60 mm $\times$ 45 mm glass–mica–glass cemented quarter-wave retarder was custom made. The fast axis of the retarder is at a 45° angle with the width of the component, which matches with the polarization axis of the microdisplay. When it is used together with the PBS, the retarder manipulates an incident linear polarization into a circular polarization and vice versa. The experimental testing of these polarization elements will be discussed in Section 6.

5. Design of a Compact Prototype

Light weight and compactness are always highly desirable features for head-mounted devices. Besides the design of a compact optical system, one of the main challenges in developing an HMD prototype is to design an ergonomically conceived and lightweight helmet, which accounts for a wide range of constraints imposed by the optical design, the electronics of the microdisplays, and various human factors.

Experiments with a first-generation prototype provided us with extremely valuable experiences and knowledge about the important human factors in particular. For example, the weight of the first-generation helmet is not well balanced. The heavy front adds significant stress to a user because it tends to pull the helmet forward and forces the user to adjust the helmet frequently. Furthermore, the enclosed top with microdisplay electronics inside causes difficulty with heat dissipation. Finally, mounting the optics in a vertical configuration leads to the overlay of ghost views directly reflected from the ground by the beam splitters. In the first-generation prototype, ground reflection is less of a concern mainly because the lighting in an environment has to be extremely dim owing to the low brightness of the virtual images. Owing to the enhancement of image brightness in our proposed p-HMPD design, the display is anticipated to function in normal room lighting conditions.

Accounting for various ergonomic factors and design constraints, we chose to mount the optics in a horizontal configuration. To avoid a front-heavy design, the optical path of the projection optics was folded 90° by inserting a mirror between the projection optics and the microdisplay [Fig. 5(a)].

Fig. 5. (Color online) Design of a compact p-HMHD prototype. (a) Overall optical layout in prototype packaging, (b) complete CAD assembly of the helmet, (c) front and (d) side views of the p-HMPD prototype.
folded design allows the installation of the microdisplay, the associated electronics, and the cables to the sides of the helmet. The folded design also contributes to the reduction of the horizontal width of the helmet and satisfies both ergonomic and aesthetic considerations. As a result, the overall width of the helmet is in proportion to the average size of an adult head, and the overall weight is nicely balanced around the head.

The total weight of the first-generation prototype is approximately 750 g. A significant portion of the weight is attributed to complex metallic optomechanical structures within the helmet, which houses the optics and provides adequate adjustments of display focusing, alignment, and IPD. To minimize the weight of the new prototype, we decided to eliminate the use of metallic optomechanical structures in the new design. Considering the free-form fabrication capability of rapid prototyping (RP) techniques, also known as layered manufacturing, we shaped the helmet shell in such a way that the necessary structures supporting the optics and electronics were integrated with the shell as one single piece. The main shell provides various shaped structures to mount the mirror, microdisplay, electronics, projection optics, PBS, and wave-plate retarder. Considering the fact that these structures were designed as an integrated piece, the positioning of these optical elements was ensured by the accuracy of fabrication, and fine positioning was warranted by spacing the adjustment during the helmet assembly.

To allow the adjustment of the IPD, the housings for the left and right arms of the optics were designed as symmetric but separate parts. The parts were connected together by two rods. By pulling or pushing the two parts, the IPD can be adjusted appropriately when necessary. This simple method eliminated the complex mechanism used in the previous design. A complete computer-aided design (CAD) assembly of the helmet shell is shown in Fig. 5(b). The left and right parts are identical, each of which consists of the main shell with the supporting structures and a cover piece. It is worth noting that the sides of the main shells were shaped to hold and guide the thick and long video cables that run from the microdisplays to a computer system.

The helmet shells were fabricated using the RP technique, in which physical models are fabricated layer by layer directly from a 3D CAD model. The helmet shells were assembled and attached to an off-the-shelf headband that offers head-size adjustment. The front and side views of the prototype are shown in Figs. 5(c) and 5(d), respectively. The total weight is approximately 450 g, significantly reduced from the previous prototype.

6. Experimental Results
The custom-made wire-grid polarizing beam splitters and the retarders were tested for FOV dependence with an Axiometric polarimeter at a 550 nm wavelength. The reflectance for S-polarized light is approximately 93% for 0° field angle, varying between 88% and 96% for field angles in the range of ±30°. The transmittance for P-polarized light is approximately 87% for 0° field angle, varying between 82% and 60% for field angles in the range of ±30°. The 0° field corresponds to a 45° incidence angle on the PBS, and a positive field angle indicates that a ray impinges on the PBS at an angle less than 45°. At the 0° field, the ratio of the reflectance for S-polarized light to P-polarized light is approximately 95, and the ratio of the transmittance for P-polarized light to S-polarized light is approximately 480.

The transmittance of the retarder is approximately constant across the entire FOV (less than 1.5% of variation). The retardance magnitude remains approximately constant up to approximately ±16° FOV and increases gradually by 40 nm (approximately 7% of the testing wavelength) at ±30° FOV. The FOV dependence of the retardance magnitude will cause a reduction of the overall efficiency at a marginal visual field of the display, creating vignetting-like artifacts.

To validate the predicted improvement on image brightness, we initially implemented two monocular prototypes on an optical bench for the convenience of testing flux efficiency: one prototype based on the polarizing design and the other without polarization manipulation using a regular 50/50 nonpolarizing beam splitter. The projection lenses used in the bench prototypes, with an effective focal length of 30 mm, were assembled from two off-the-shelf achromats.

Using a calibrated, collimated light source, we quantified the luminance efficiency of the two bench setups over ±30° of the FOV. The experimental results demonstrate approximately four times of consistent improvement on luminance efficiency, across the entire FOV. Combining the efficiencies of the projection optics, the PBS, the retarder, and the retroreflective film, the overall efficiency of the polarized setup is approximately 17% at the center field and slowly drops down to approximately 12% at ±30° fields. On the contrary, the overall efficiency of the nonpolarized setup is approximately 4% at the center and drops down to approximately 2% at ±30°. Further measurements will be made for other wavelengths. A comprehensive analysis of the above polarimetric properties and luminance efficiency quantification as well as their impacts on image quality will be reported in a follow-up article.

To compare the image brightness and contrast of the two setups with and without polarization control, the collimated light source used in the previous testing was replaced with microdisplays, and an identical image was projected through the setups. Under identical room lighting conditions and camera exposure settings, a set of photographs was taken from the two bench prototypes by aligning the camera with the exit pupil of the optics. Two examples of the photographs under identical room lighting from the polarized and the nonpolarizing displays are shown in Figs. 6(a) and 6(b), respectively. It is worth noting that neither postprocessing nor brightness enhancement was performed on these photographs. The photographs from
the polarized setup demonstrated a considerable increase in intensity and significant improvement in image contrast and color vividness over those from the nonpolarizing setup.

From the photograph sets, we analyzed the histograms of the region representing the display view, which is marked with dotted circular lines in the figure. The histograms for the two examples in Figs. 6(a) and 6(b) are shown in Figs. 6(c) and 6(d), respectively. The mean intensity values increase by approximately 50%, from 78 for the nonpolarizing HMPD design to 111 for the p-HMPD, and the standard deviations increase by approximately 52%, from 21 to 33. Such wider intensity distribution for the p-HMPD indicates an improvement in image contrast and dynamic range.

7. Conclusion and Future Work

In this paper we presented the design of a p-HMPD with considerably improved luminance efficiency compared with existing HMPD designs. The luminance efficiency of the proposed design is approximately three times brighter than a nonpolarizing design. The paper also detailed the optical system and helmet design for a compact head-mounted prototype. In future work, experiments will be performed to characterize the depolarization effects of the retroreflective material, quantify the chromatic dependence of the polarization elements, and quantitatively evaluate the luminance efficiency and the chromatic responses of the display. We will also custom design a high-resolution, brighter display prototype using LCOS-based microdisplays for more demanding applications.

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