Abstract
We have designed a compact light engine for a ferroelectric Liquid-crystal-on-Silicon (FLCOS) microdisplay used in a polarized head mounted projection display (p-HMPD). In the light engine, the polarization of the light is manipulated in order to achieve a compact structure and a mirror based tapered light pipe is designed to improve the light efficiency and image uniformity. The performance of the light engine is analyzed based on the simulation results using LightTools.

1. Introduction
Optical see-through head mounted displays (HMDs) have been widely used for three-dimensional visualization tasks such as surgical planning, medical training, or engineering design. However, it has been a common problem in optical see-through HMDs that the displayed image lacks image brightness and contrast compared to the direct view of a real-world scene. This problem becomes aggravated in head-mounted projection displays (HMPD) in which light is split multiple times through a beamsplitter. For instance, with a miniature backlit active matrix liquid crystal display as the image source, the luminance of the observed image is estimated to be 4 cd/m$^2$, while the average luminance of a well-lit indoor environment is over 100 cd/m$^2$. As a result, the low-brightness image of HMPDs will appear washed out in such well-lit environments. In fact, most optical see-through HMDs, including HMPD, are typically operated under a dimmed lighting condition.

To address this problem, a polarized head-mounted projection displays (p-HMPD) based on the transmissive LCD microdisplay was designed recently [1]. By carefully manipulating the polarization of the light, p-HMPD is three times brighter compared with a non-polarized HMPD design. A schematic design of a monocular p-HMPD configuration is illustrated in Fig. 1. The image on the LCD display is projected through the projection lens, forming a real intermediate image. The light from the LCD is manipulated to be S-polarized so that its polarization direction is matched with the high-reflection axis of the polarized beamsplitter (PBS). The polarization state of the reflected light is then manipulated by a quarter-wave retarder and is converted into circular polarization. The circularly polarized light is then retroreflected back by a retroreflective screen. Passing through the same retarder, the circularly polarized light is converted to P-polarization and transmits through the PBS with high efficiency. Thus the projected image from the microdisplay can be then observed at the exit pupil of the system, which is conjugate with the exit pupil of the projection lens.

However, since a transmissive LCD microdisplay has low transmission efficiency of around 5%, the overall performance of current p-HMPD is still unsatisfactory in a well-lit environment. To get high luminance and high image quality, we have designed a new p-HMPD using a ferroelectric Liquid-crystal-on-Silicon (FLCOS) microdisplay (Forth Dimensional Displays Limited). The FLCOS microdisplays operate in reflective mode, opposed to the transmission mode of backlit LCDs, has higher luminous efficiency but requires a light engine to illuminate the microdisplay. Thus, designing a light engine with high performance and compact structure is the key to a successful p-HMPD system. In this paper, we will describe the design of the light engine and evaluate the performance of the light engine in details. We will also demonstrate the prototype of the new p-HMPD.

2. The design of the light engine
2.1 Design requirement
In the previous design of a p-HMPD prototype, a 1.3” color LCD with a resolution of (640*3)*480 pixels was used as the image sources. To design a system with higher luminance and better image quality, we select the SXGA-R2D FLCOS microdisplay kit by Forth Dimensional Displays Limited as the image source. The usage of FLCOS microdisplays makes the optical design of a p-HMPD quite different from the previous designs of p-HMPD optics [2]. One of the key differences is the requirement for illumination units. The FLCOS microdisplay works most efficiently when the illumination rays are normally incident upon the display surface. To ensure the high contrast of the output image, it is recommended to limit the incident angle to the range of $\pm 16$ degrees [3], which imposes a critical requirement on the design of both a light engine and a projection lens. The key requirements for the illumination engine include: (1) the illumination system is image-space telecentric to ensure that for every pixel on the display surface the incident chief ray is normal to the display surface and (2) the cone angle is smaller than 16 degrees.

2.2 Light source
Table 1. Specification of microdisplay and LED illuminator

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
<th>Parameters</th>
<th>Specification</th>
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<tbody>
<tr>
<td>FLCOS microdisplay</td>
<td></td>
<td>LED panel</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>22.3mm</td>
<td>Body Dimensions</td>
<td>18.4 x 14.1mm</td>
</tr>
<tr>
<td>Active area</td>
<td>17.43 x 13.95 mm</td>
<td>Active area</td>
<td>8.4 x 6.5mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>1280x 1024 pixels</td>
<td>Weight</td>
<td>4 ± .5 grams</td>
</tr>
<tr>
<td>Pix size</td>
<td>13.6 μm</td>
<td>Luminance</td>
<td>34800 (cd/m²)</td>
</tr>
<tr>
<td>Color technique</td>
<td>Field sequential color</td>
<td>Color Coordinates</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Red: x = .67-.43, y = .27-.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Green: x=.14-.28, y = .64-.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blue: x = .11-.15, y = .04-.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Power</td>
<td>340mW</td>
</tr>
</tbody>
</table>

The light source selection is the first step in the light engine design. Based on the design requirement of a HMPD, there are several constraints on the source selection and the light engine design. First, safety is a primary concern in any head-mounted devices. Therefore sources with low power consumption and low heat dissipation are highly desired. Secondly, compactness and lightweight are always critical for HMD systems. Finally, in order to generate an image with high brightness and uniformity across the whole FOV, the illumination on the microdisplay should be uniform and bright. A 0.5” Alphalight® color LED illuminator by Teledyne Inc. is selected for our p-HMPD prototype design [4]. The illuminator is compatibly driven by the color sequential technique of the FLCOS displays. Table 1 summarizes the major specifications of the microdisplay and illuminator.

![Fig. 2. Luminance distribution of LED illuminator](image)

**2.3 Schematic design of light engine**

Fig. 2 shows the angular luminance distribution of the LED panel. The luminance distribution of the Alphalight LED panel is relatively uniform, and the luminance is highest at the normal direction of the panel and drops by about 17% at an 18° emitting angle [4]. Figure 3 shows the schematic design of our light engine to meet the requirements for image-space telecentricity, compactness, high efficiency, and uniformity. The LED illuminator is placed at the focal point of a concave reflector. In order to achieve compactness, we use a PBS to fold the optical path in half and the microdisplay is placed conjugatedly at the focal point of the reflector. A polarizer is placed in front of the LED panel so that S-polarized light is reflected by the PBS toward the reflector. A quarter-wave retarder is placed between the reflector and PBS and its fast axis is at a 45° angle with the S-polarized light. By passing through the retarder twice, the reflected light by the reflector becomes P-polarized and is transmitted through the PBS to illuminate the microdisplay with high efficiency. Due to the quarter-wave retarder nature of the FLCOS microdisplay, the reflected light by the microdisplay becomes S-polarized and is reflected toward the projection lens by the PBS.

![Fig 3. Schematic design of a light engine.](image)

In this design, the LED panel itself can be taken as the stop of the system to form an image-space telecentric system and the ray bundle received by the display is symmetric with the display normal. With both source and microdisplay at the focal point of the reflector, the light distribution on the microdisplay is the Fourier transform of that of the LED. Thus the spatial distribution on the microdisplay can be derived by

\[
E_{display}(x,y) = L \cdot \Omega = L_{LED} \cdot \left( \arctan \left( \frac{\sqrt{x^2 + y^2}}{f} \right) \right) \cdot \frac{S_{LED}}{f^2} \tag{1}
\]

where \( E_{display}(x,y) \) is the illuminance at the \((x,y)\) on the display assuming the center of the display is at the origin, \( L_{LED}(\theta) \) is the luminance of LED as a function of angle, \( S_{LED} \) is the area of the LED panel and \( f \) is the focal length of the lens. Across the display panel, the ratio of the luminance at the center of the display to that
at the edge is \( L_{LED}(0^\circ) / L_{LED}(\text{arctan}(D/2f)) \) while \( D \) is the diagonal size of the display. To get better uniformity on the display, a lens with larger focal length is preferred. But meanwhile, larger focal length will result in a less compact structure and a smaller solid angle with lower luminance efficiency. By considering all these factors, we select a reflector with 35mm focal length and 35mm diameter. As a result, the ratio of the maximum luminance to the minimum luminance on the display is 1:0.82, and cone angle of the ray bundle on the display is within 8.6 degrees. The light within cone angle of 18 degrees emitted by the LED can be collected by the reflector to illuminate the display while the light with larger angle is wasted.

In order to further improve the light efficiency and the uniformity of the light engine, we designed a mirror-based tapered light pipe to recycle the light with emission angles larger than 18 degrees. Figure 4(a) shows a prototype design of the light pipe. It is composed of four mirrors, each of which is tilted by an angle with the LED surface, forming a truncated pyramid shape. The light emitted from the LED with large angles will be reflected by the enclosed mirror. After reflection, more rays from LED can be collected by the lens system to illuminate the microdisplay. To get the best performance of the light engine, both tilt angle \( \alpha \) and mirror length \( t \) of the mirror, as shown in figure 4(b), should be optimized.

### 2.4 Simulation

To determine the parameters of the tapered light pipe and to examine the light efficiency and uniformity of the light engine, we modeled the light engine using LightTools® [5]. In the simulation, the total power of the source was set to be 1 lumen. A light receiver was placed on the microdisplay to estimate the efficiency of the light engine and to evaluate the light distribution on the microdisplay. Through the simulation, it indicates that the light engine has higher uniformity and light efficiency when the tilt angle of the mirror is at 18 degrees. By balancing the performance and space constraint of the light engine, the mirror size \( t \) is selected to be 8mm. Fig 5(a) and Fig 5(b) show the output illuminance distribution on the microdisplay for system without and with the mirror based light pipe, respectively.

As indicated by the simulation results, with a mirror based light pipe, the light efficiency has increased from 8.93% to 12.3%, and the non-uniformity, quantified by the average standard deviation of the illuminance distribution across the display area, has reduced from 5.61% to 2.15%. It means the system with the light pipe has higher efficiency and better uniformity.

### 3. p-HMPD Prototype

Based on the design of the light engine, we designed a lightweight and compact telecentric projection lens with an overall length of 34mm, and weight of 8.2 grams. All the elements are plastic to get a lightweight system. The lens is image space telecentric and has 55 degree field of view. A diffractive optical element (DOE) is used to help correct chromatic aberration [6]. The RMS spot diameter for the lens is averagely about 16 \( \mu \)m and the MTF at threshold spatial frequency 37 cycle/mm (i.e. \( 1/(2*\text{pixel size}) \)) is about 40% across the entire field of view. This lens is fabricated by the Apollo Optical System.

With the design of light engine and projection lens, we further designed a compact prototype of p-HMPD. Figure 7 shows the side views of the p-HMPD prototype.

### 4. Conclusion
The design of illumination systems for reflective LCDs has been well explored in digital projector industry [7]. However most of the designs require a long optical path and is too bulky to be used for head-mounted applications. In this paper, we have presented a compact light engine design for FLCoS displays. Compared with our previous design using double telecentric optics [2], this design is more compact and has better performance. With a mirror based light pipe, we are able to considerably improve the light efficiency and uniformity.

5. Acknowledgement
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6. References