Optical Modeling of a Holographic Single Element Head-mounted Display

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ABSTRACT

This paper proposes a new method to design an optically-fabricated holographic element, where the construction optical system and the playback system can be optimized jointly. The method was driven by the use of a new holographic recording material – the photo-thermo-refractive (PTR) glass - that can only be written at 325nm, while its playback takes place in the visible part of the spectrum. Applying the method proposed, a single holographic element head-mounted display (HMD) was modeled. Results show that a single holographic element may be constructed at 325 nm, and inserted in a playback optical system operating at 633nm, with a MTF of over 80% across a 40 degree field of view at 37cycles/mm.

Keywords: optical design, holographic element, PTR glass, head-mounted display

1. INTRODUCTION

With the rapid development of research in virtual environments and simulation, the design of light and compact head mounted displays (HMDs) is the Holy Grail. To achieve compactness many efforts have been made, such as incorporating aspherical elements, plastic elements, and diffractive optical elements (DOEs).[1,2] Volume holographic elements have also been employed in HMD design, but mainly as optical combiners.[3] Volume holographic elements are thick phase gratings usually produced by interference fringes in a relatively thick emulsion (i.e. 5 to 30 microns) such as dichromated gelatin (DCG). Due to the chemical properties of the emulsion, the fabrication of such holographic elements is always a complicated process.

Recently a new holographic material named photo-thermo-refractive (PTR) glass has emerged,[6,7] which overcame several disadvantages of the conventional emulsion. Properties of PTR glass allow recording of volume holograms with 98% of diffraction efficiency in a 1 mm thick glass plate. [8, 9] The only drawback of this material is its region of photosensitivity that is restricted to the UV region.

In this paper we propose novel mechanisms of hologram recording and reconstruction that would allow designing holographic optical elements (HOEs) in PTR glass for playback in the visible and the IR regions of the spectra by the usage of corrective optical elements. This concept paves the way for novel types of HMDs with a single transparent element as the imaging optics. The single element investigated is a doublet which consists of one conventional positive lens and a holographic optical element (HOE) made of PTR glass. Unlike the classic HOE in which the phase profile is generated as the interference of two spherical wavefronts, non-spherical wavefronts are employed in the construction of the HOE in our design. With the modeling method we present, the construction system and the playback system with the HOE can be designed and optimized jointly. In section 2 the modeling method is presented, and in section 3 an example of a design of a holographic single element eyepiece for HMD based on such method is provided.

2. METHOD

The classic HOE is defined by the construction wavelength (λ_C) and the location of two point sources (i.e. X_O, Y_O, Z_O for the object point, and X_R, Y_R, Z_R for the reference point) during the construction or recording process. In the playback or readout mode, the HOE is illuminated by a wavefront and produces a modified wavefront through diffraction. From a designer perspective as opposed to a user perspective, the playback system is considered first because it must be

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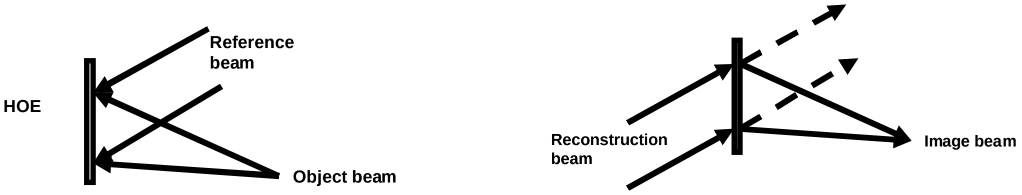
designed first, and the construction system is designed last. Therefore, we will throughout the paper refer to them in this order. During the design of optical systems with classic HOEs, the vector grating diffraction equation [4] as shown in Eq. (1) is used for ray tracing.

$$\mathbf{n}\times(\mathbf{r_I}-\mathbf{r_D})=\frac{m\lambda_P}{\lambda_C}\mathbf{n}\times(\mathbf{r_O}-\mathbf{r_R})\ , \tag{1}$$

where $\boldsymbol{n}$ is the surface normal vector for the HOE surface, $\boldsymbol{r_O}$ and $\boldsymbol{r_R}$ are the unit vectors from the object and reference point sources to a point on the HOE, respectively, $\boldsymbol{r_I}$ and $\boldsymbol{r_D}$ are the unit ray vectors for the incident and diffracted rays during the playback mode, respectively, λ_P and λ_C are the wavelengths used for the playback and construction modes, respectively, and m is the diffracted order number for the HOE. Fig. 1(a) shows a classic HOE generated by the interference of two beams from two point sources. Fig. 1(b) shows the same HOE in its playback mode.



(a) (b)

Figure 1 Classic two-point HOE

By definition, a non-classic HOE is generated by the interference of two non-spherical wavefronts. The parameters in Eq. (1) cannot fully describe a non-classic HOE in optical design. A continuous phase profile function $\phi(x, y)$ needs to be introduced to define the non-classic HOE, where x, y are the coordinates on the HOE surface, and ϕ is in lens unit. For rotationally symmetrical HOEs which are most common in optical design, we can use a rotationally symmetrical polynomial to define the phase profile [5]

$$\phi=\sum_{n=1}^{i}C_n r^{2n} \quad , \tag{2}$$

where r is the radius of the HOE surface, and the coefficients C_n are the phase terms for different orders. The standard grating equation is then used to get α_m -- the direction of the diffracted ray in the mth order given by

$$\sin\alpha_m-\sin\alpha_I=m\lambda_P\Lambda(r)\,, \tag{3}$$

where $\Lambda(r)$ is the derivative of the phase function which is a function of the radius on the HOE surface, α_I is the angle of the incident rays, and m is always +1 or -1 in volume HOEs.

A non-classic HOE generated by two non-spherical wavefronts can be modeled as a nominal classic two-point HOE followed by a nominal kinoform which can be defined purely with a phase profile function. To perform the ray tracing, we apply the vector grating equation to the classic HOE first, and then take the derivative of the phase profile to get the localized fringe frequency of the kinoform. The standard grating equation is then applied to get the direction for the diffracted ray. Therefore, the parameters for modeling a non-classic volume HOE are: the construction wavelength, the diffraction order number, the coordinates of two point sources for the nominal classic HOE, and a set of coefficients for the phase profile function for the nominal kinoform.

In optical design, we need to use the HOE surface in both the playback optics and the separate construction optics to improve the system performance, and provide for highly corrected point-to-point imaging in the construction optics. Thus, when designing an optical system with a volume HOE, three optical systems must be designed --- two for the construction mode and one for the playback. By conveying parameters of the HOE among these optical systems, we can design and optimize them jointly.

3. DESIGN EXAMPLE

We employed a transmissive liquid crystal display (LCD) as the image source for the HMD. Table 1 lists the lens specifications of the HMD we designed in a feasibility study. The single element of the optics is a doublet consisting of a conventional lens made of BK7 glass and an HOE made of PTR glass. Because of the nature of the PTR glass, the HOE construction wavelength is set to 325nm.

Table 1 Design Specification

Parameter	Specification
Object: Monochromatic LCD	
a. Size	0.7 inch diagonal
b. Active display area	Rectangular, 14.33mm x 10.75mm
c. Resolution	1024 x 768 pixels
d. Illumination light	633 nm
Eyepiece:	
a. Type	HOE hybrid
b. Focal length	24.72 mm
c. Exit pupil diameter	5 mm
d. Virtual image distance	Infinity
e. Eye relief	23 mm
Other parameters:	
FOV	40° in diagonal

Firstly we started with the playback system as shown in Fig.2. During the design we controlled the effective focal length of the system and set the curvature and HOE parameters to be variables. After the optimization, the HOE parameters were set as given in Table 2.

Table 2 HOE parameters after first optimization

Parameters	Values
Construction Wavelength	325 nm
Diffraction Order	1
Two points for the classic HOE	
Object (X_O, Y_O, Z_O)	(0, 0, -14.10)
Reference (X_R, Y_R, Z_R)	(0, 0, -1e20)
Kinoform Parameters	
C_1	2.62e-2
C_2	-4.38e-5
C_3	1.04e-7
C_4	-2.45e-10

As shown in Table 2, the two point sources are both on the left side of the holographic surface, which makes the element a transmissive HOE. The coefficients of the phase profile function are for a rotationally symmetrical kinoform which can be described with Eq. (2).

After completing a preliminary design of the playback system, we built a point-to-point imaging system with the HOE from the last step shown in Fig. 3. The system consisted of two aspherical elements on each side of the HOE. The input beam was a collimated beam from infinity and the output beam was also designed to be collimated. To evaluate the aberrations, an ideal lens was set behind the last surface of the right lens. During the design, we first froze the HOE parameters and optimized the optical system to minimized aberrations. With the aspherical surfaces we had in the system, the error function was driven to a very small value. We then froze all the parameters and varied the coefficients of the HOE C_1 to C_4. After one more optimization, the error function was driven to zero and the coefficients of the HOE changed slightly to the new values listed in Table 3.

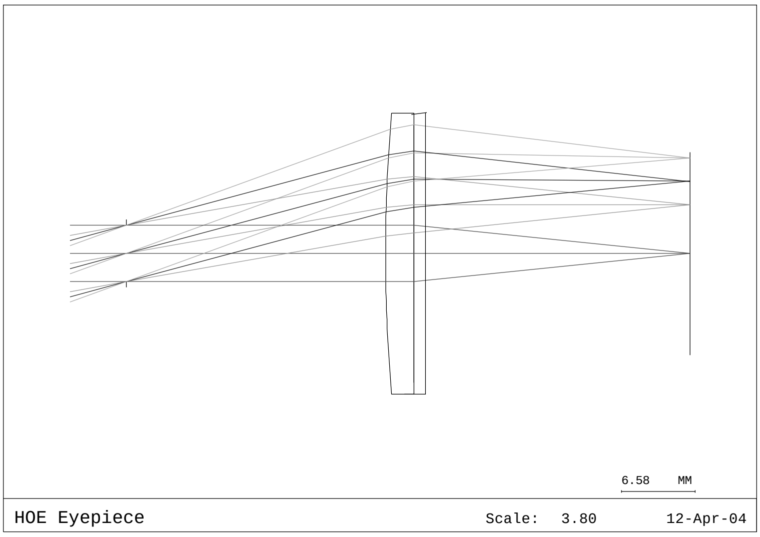


Figure 2 Layout of the HMD system

Table 3 Optimized phase terms for the final system

Coefficients	Values
C_1	2.59e-2
C_2	-4.41e-5
C_3	1.04e-7
C_4	-2.43e-10

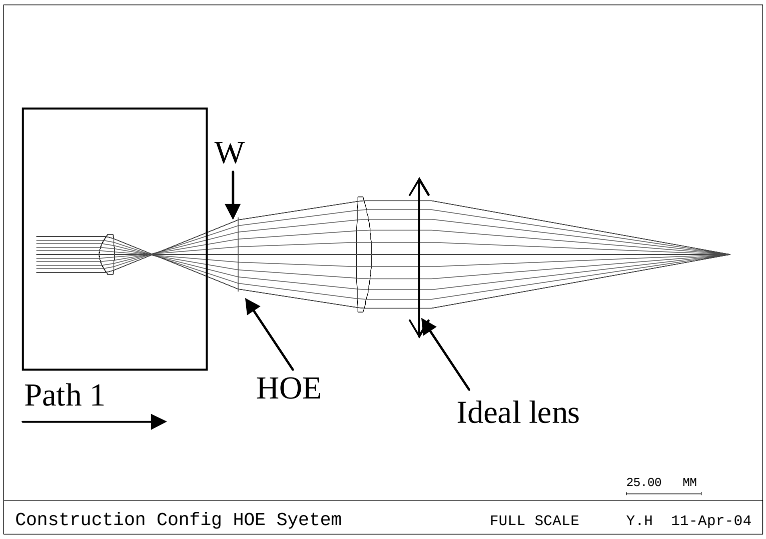


Figure 3 Layout of the optical system to generate the 1st construction wavefront

In the optical layout of Fig. 3, the HOE is illuminated by a wavefront from the left. After passing the HOE, the wavefront is modified to become another wavefront W on the right. The two wavefronts on each side of the HOE are the two construction wavefronts to be used to interfere on the holographic PTR glass recording material. The left hand side of the system in Fig.3 is the optical path to generate the first wavefront for construction.

While the wavefront W is the second wavefront for construction, however the right hand side of the optics in Fig. 3 is not the optical path we need to generate the second required wavefront for construction. Since the HOE is a transmissive element, we need to generate the second wavefront *W* from the left hand side of the recording material. As we extend the rays from the right hand side of Fig 3, we obtain the optical layout shown in Fig 4, where the dummy surface indicates the location of the previous HOE. It is not a perfect point at the extension of the rays, which indicates that the wavefront *W* is non-spherical. To generate the non-spherical wavefront *W*, another point-to-point imaging system needs to be designed based on the optics in Fig 4.

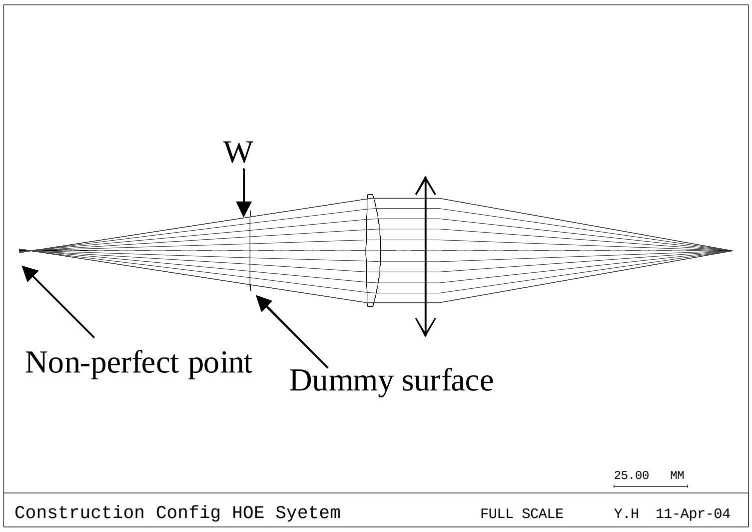


Figure 4 A non-perfect point formed by extending the rays

We flipped the optics in Fig. 4 and added some patching optics on the other side of the dummy surface. We then optimized the system to make the output beam perfectly collimated by adjusting the aspherical parameters of the patching optics as shown in Fig 5. By flipping the patching optics in Fig. 5, we get the optical path for generating the second construction wavefront W.

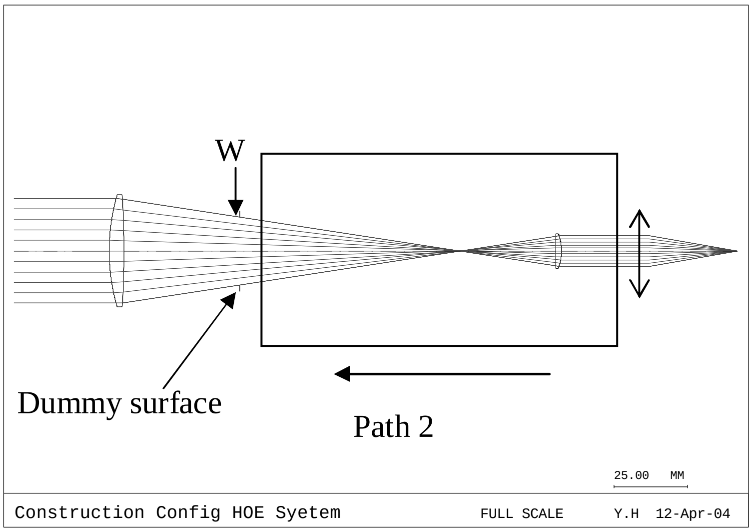


Figure 5 Layout of the optical system to generate the 2nd construction wavefront

By combining the two optical paths in Figs. 3 and 5 with a beam combiner, we get the optical layout for the construction optics as shown in Fig. 6.

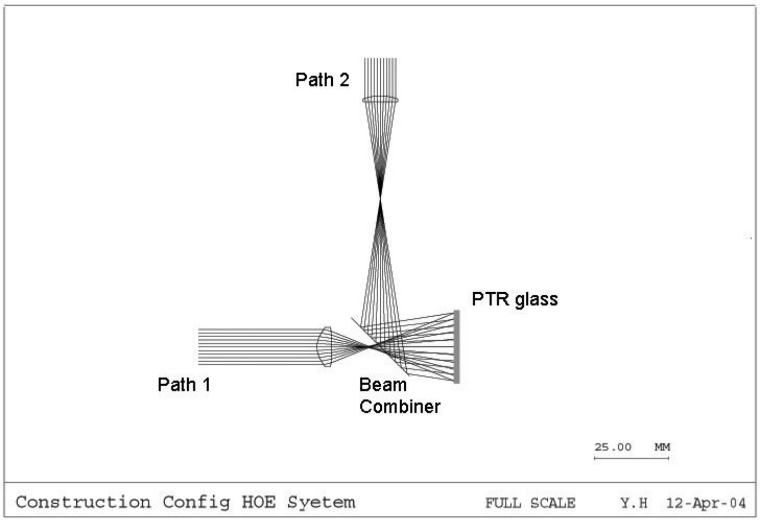


Figure 6 Optical Layout for the construction of HOE

After designing the construction optics, we transferred the slightly changed coefficients in Table 2 back to the playback system. We froze all the HOE parameters and varied the radius of the first surface for a final optimization. Since the change in the HOE coefficients is extremely small, the layout of the system remained similar to that shown in Fig. 2.

Fig. 7 shows the modulation transfer function (MTF) of the system, which holds well across the FOV and reaches about 80% at 37 lp/mm which corresponds to the resolution of the miniature display. This indicates that the optics itself will not limit the resolution, but the image source will. Fig. 8 shows the distortion of the optical system. Results show barrel distortion and the largest value across the FOV was quantified to less than 6.5% in this case.

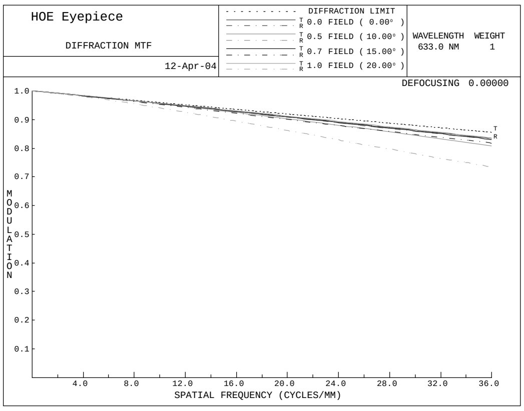


Figure 7 MTF performance

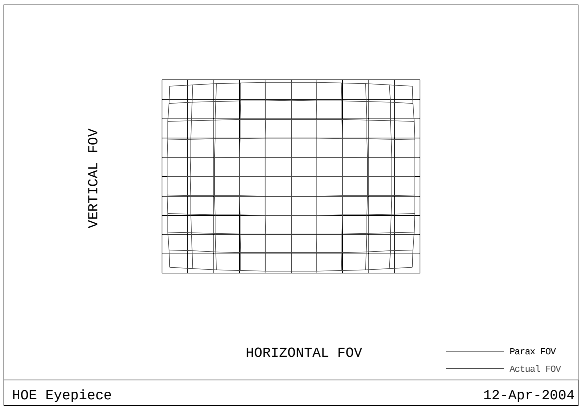


Figure 8 Distortion performance

4. CONCLUSION

By modeling a non-classic volume HOE as a classic two-point HOE followed by a kinoform, construction and playback systems with a HOE can be designed and optimized jointly. An HMD system with a holographic single element was designed with this modeling method. High performance (i.e. >80%) in MTF was achieved across a 40° FOV. It was beyond the scope of this paper to include an analysis and optimization of the efficiency of the HOE. It will be discussed in detail with the PTR glass in future work.

5. ACKNOWLEDGMENTS

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