HOLOGRAPHIC CURVED WAVEGUIDE COMBINER FOR HUD/AR

by

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This thesis contains efforts toward head up display and augmented reality devices using combiners comprised of holographic optical elements on waveguides.

Holographic optical elements couple image bearing light beyond total internal reflection conditions within a planar waveguide. The pupil is expanded in 2 dimensions while magnifying the image to produce a head up display with smaller form factor and large field of view over an expanded eye box [1].

Aberration in the form of image duplication is seen in pupil replicating waveguide combiners which were examined and realized to be from the conditions of the internally propagating light. The internally propagating light should be collimated, and a solution is proposed for multiple depths of field to be projected into the viewer’s field of view free from aberration [2].

A method is presented for image propagation through a curved waveguide combiner with pupil replication. The insertion holographic optical element imposes astigmatic power to mitigate propagation aberrations. An extraction holographic optical element outcouples the image over an expanded eye box [3].

Abstract
Chapter 1
Introduction

1.1  Background

Head up displays (HUDs) and near to eye displays (NEDs) provide numerous benefits for many applications from education to improved situational awareness to increased productivity and have become increasingly popular research area due to the increase of computation power available to the population [4]. This category of displays allows for the display of virtual information on top of the natural world [5]. Benefits can include improved situational awareness or more diverse applications which can include social media, learning and teaching methods and gaming [1]. They offer the ability to improve productivity by displaying relevant information at the task at hand and offer an improved bridge for human-computer interaction. Human visual cues and computing power are some factors which should be satisfied for augmented reality. A head up displays system’s properties of footprint, field of view, eyebox, comfort, efficiency and whether it is varifocal are dictated by the projector and combiner.

Augmented reality has been realized to improve education methods by increasing student’s motivation and interest while providing information which cannot be easily observed [4]. Such a display allows a student to be immersed in the information for a true learning experience. Complex physical phenomena can more easily be explained when a student can interact with virtual
information through a HUD or NED. Training can be implemented using AR simulations to place trainees within environments to develop their required skills in certain situations.

Situational awareness leads to higher levels of safety, and this can be increased in vehicle operators by a head up display system [1]. A head up display allows operators to remain focused on the surroundings rather than on an internal readout. This increases eyes forward time and can reduce reaction time as relevant information is projected into view [6, 7, 8, 9, 10].

A waveguide combiner can decouple the field of view from the eyebox leading to a smaller footprint due to a smaller projector required [1]. This technique is referred to as pupil expansion. A waveguide combiner replicates the input pupil across the length of an extraction hologram by outcoupling a portion of the light. This light is then recirculated to outcouple in subsequent reflections effectively replicating the input pupil. An expanded eye box is beneficial as a user of a head up display to reduce the need to constantly keep themselves aligned with the system. This increases the comfort of the user by allowing for use with natural user movements.

The human visual cues can be satisfied in waveguide combiner displays by using multiple waveguides where each relays a unique depth [2]. As different depths of field are relayed through a single waveguide combiner, an image doubling aberration occurs across the expanded pupil reducing the resolution at small differences and noticeable image doubling at large variations. Disorientation can occur if the visual cues are not satisfied due to accommodation-vergence conflict [11, 12]. It is important to display a virtual image which produces the visual cues of accommodation, vergence, motion parallax and occlusion.

The comfort of a near to eye display can be realized with curved waveguides for social acceptance and form factor [3]. As AR technologies increase, the location of use will be changed
from a private setting, like a home, to public settings. For this change, the near to eye display must be socially acceptable. For an AR system to be socially acceptable, it should have a small form factor, and have a similar curved shape of current glasses or sunglasses. This involves a curved glass appearance as flat does not look like standard eye wear. There have been attempts to put an extra curved substrate barrier over the flat waveguides to make them more visually appealing such as the Magic Leap 1 headset from Magic Leap or the HoloLens 2 from Microsoft, but this adds more bulk to the system. The pupil replication through the combiner allows for a smaller projector to be used which as well reduces the overall NED footprint to be more socially acceptable.

1.2 State of the Art Combiners

There are numerous combiner methods in research and on the market. Among the different types of combiner elements for AR and MR application, one can find beam splitter, dichroic mirror or hologram to mix the virtual and real environment. Typically, a beam splitter and dichroic mirror act as a simple reflector that put the last optical element further from the viewer which limits the FOV. The use of freeform optics as well as holographic optical elements, allows the combiner to act as the last lens of the system which, every other aspect being kept equal, permits a larger FOV. However, in all these systems, FOV and eyebox product is proportional to the finite space-bandwidth product which implies as when one increases the other decreases [13]. When using a waveguide to propagate the image, the light recycling inside the waveguide and the pupil replication allows to decouple FOV and eyebox, since now the eyebox can be as large as a windshield.

Curved combiners have been limited to either a curved reflector or a waveguide approach with no pupil expansion because the power between each exit pupil is different [14].
1.3 Proposed Combiner Method

A combiner based on HOEs can impart a correct wavefront for waveguide propagation and extract an image. A 2-D pupil expansion vastly reduces the required projector size by expanding the eye box in 2-D which is discussed in Chapter 2. A projector is also optional to form an image with an insertion hologram with infinite image magnification which allows for a display to be the object of the combiner system. A parameter which creates the artifact of image duplication across an expanded pupil was determined to be uncollimated internally propagating light within the waveguide in pupil replicating systems discussed in Chapter 3.

A curved combiner with pupil replication allows for the advantages of pupil replication which include larger eye box and field of view and the advantages of a curved substrate which include social acceptance and better conformity to be integrated into systems. A correction is imparted into the insertion hologram to diffract the light to TIR through the curved waveguide in a quasi-collimated state to be extracted multiple times across an expanded pupil with little power difference between each exit pupil discussed in Chapter 4.
Chapter 2
Holographic Waveguide Head-Up Display with 2-D Pupil Expansion and Longitudinal Image Magnification

This chapter describes a method of creating a combiner for head up display with 2D pupil expansion and longitudinal image magnification using holographic optical elements on a planar waveguide. Lateral magnification approaches infinity because the HUD projects a virtual image at infinity.

2.1 Background

Head up displays are being deployed in transportation vehicle such as automobiles and aircraft to reduce the amount of time spent looking away from either the road or sky in comparison to a head down display. This advantage helps improve the pilot situational awareness, and reduces reaction time [6, 7, 8, 9, 10]. There exist many versions of HUDs, the simplest of which consist of using a smartphone sitting on a dashboard with the image reflected by the windshield into the driver’s eyes. Unfortunately, this version does not provide the image at the same focal distance as the road, forcing the eye to accommodate. The current avionics HUD uses a combiner with a dichroic mirror or a hologram, to reflect a collimated image into the user’s eyes. This method effectively superimposes an image onto the far field by using a system of lenses to expand and collimate an image from the projector as seen in Figure 2.1. [15, 16].
The limitations of the traditional airliner HUD stem from the footprint of the system where the field of view (FOV) or perceived image depends on the size of the projection optics. In areas such as an avionics cockpit or automobile dashboard, space is severely restricted forcing an ultimate limit on FOV achievable. Another issue is the narrow area where an operator can view the entire projected image. This area is called the eye box and is determined by the triangle formed by the image (located at infinity), the surface of the combiner, and the viewer location presented in Figure 2.1. Accordingly, the larger the combiner, the larger the eye box and FOV can potentially be.

These limitations on the footprint of the system, eye box size, and FOV in traditional HUDs have researchers looking for other solutions such as freeform optics, multi-mirror elements, and waveguides [17, 18, 19, 20]. Here, we present an original HUD configuration with a small footprint that uses holographic optical elements (HOEs) in combination with waveguide optics to increase both the eye box and the FOV while keeping the image projected at infinity.
Figure 2.1. Traditional aircraft HUD with holographic combiner for image projection [1].

Figure 2.2. shows the configuration of the HUD system we pursued, where three edge lit HOEs on a waveguide effectively reduced the HUD size while still offering a wide FOV over a large area. This is accomplished by inserting an image into the waveguide using an insertion hologram that has optical power to collimate and diffract the image. The diffraction angle is such that the light is coupled inside the waveguide by total internal reflection (TIR) and propagates horizontally along the length of the waveguide.
Figure 2.2. Conceptual design of the HUD system showing the different hologram sections that couple the image inside the waveguide, redirect it internally, and extract the light with two-dimensional pupil expansion for an increased eye box [1].

The light is then redirected vertically along the length of the waveguide with a second hologram while keeping the TIR condition. The diffraction efficiency of the redirection hologram is less than a 100% so the light that is not redirected continues its travel inside the waveguide and is only redirected after further interaction with the hologram.

The light that is now propagating vertically is then diffracted toward the viewer thanks to an extraction hologram. The light that is not diffracted after the first interaction with this hologram continues its travel inside the waveguide in the vertical direction and is eventually
extracted after further interaction with the hologram. The efficiency profile of the redirection and extraction holograms will be discussed in section 2.2.2.

By recirculating the light several times within the waveguide, the redirection and extraction holograms expand the pupil in the horizontal and vertical directions, respectively. It is to be noted that this pupil expansion does not change the image magnification, which is only due to the optical power of the insertion hologram. Also, since the image is focused at infinity, multiple extractions do not replicate the image but expand the eye box. From the viewer perspective, the HUD system presents a single, collimated, magnified image across an expanded eye box.

Figure 2.3. shows the process of pupil expansion in one-dimension where an image is coupled into a waveguide beyond TIR conditions and splits along the extraction hologram to achieve multiple extractions of the same image.
2.2 Hologram Design

Our HUD system consists of three edge-illuminated holograms labeled the insertion, the redirection, and the extraction. The holograms are applied onto a planar waveguide surface. The specifics of each hologram are as follows:

2.2.1 Insertion Hologram

The insertion hologram is designed such that it has optical power and redirects the image inside the waveguide at TIR. The hologram collimates a diverging beam located in front of the waveguide surface and redirects it within the waveguide. This angle allows the diffracted beam to propagate internally without overlap or gaps between reflections concerning the size of the...
hologram and waveguide thickness. Encoding optical power into the insertion hologram removes
the need for optics to magnify the image and optics to locate it at infinity. A drawback of this
approach is a full color display will have only one color across the FOV in focus because of the
chromatic aberration from a single HOE.

2.2.2 Redirection Hologram

The redirection hologram was designed to receive the collimated beam propagating
horizontally inside the waveguide and diffract it in the vertical direction. The angle allows
propagation without overlap or gaps between the different TIR bounces, which would result dark
areas in the projected image. As angle of incidence varies, the light diffracted to total internally
reflect varies as well and leads to gaps in the extracted light at angles that propagate greater than
the center insertion angle. Simulation has shown that these dark spots are resolved using a
reconstruction source with a spectrum associated with it as angle which light propagates changes
with wavelength.

The pupil is expanded laterally by the multiple diffractions of the image across the length
of the hologram. To ensure a uniform image intensity through the entire pupil, the diffraction
efficiency (DE) varies across the width of the hologram. Each time the light interacts with the
hologram, some portion is diffracted, which leaves less intensity inside the waveguide to be
diffracted by the subsequent interactions.

If \( I_0 \) is the initial intensity injected inside the waveguide, and \( N \) is the number of
extractions, the maximum uniform image intensity is given by \( I_0/N \). The residual light
propagating inside the waveguide after the first interaction is \( I_0-I_0/N \), after the second interaction
this intensity is \( I_0-2I_0/N \), and after the \( n^{th} \) interaction it is \( I(n)=I_0[1-(n-1)/N] \). To have constant
intensity diffracted by the hologram while the incident intensity \( I(n) \) decreases, the DE of the
different sections of the hologram should increase such that \( DE(n)I(n) = I_0/N \) or \( DE(n) = 1/(N-n+1) \).

Figure 2.4 shows the diffraction efficiency profile (red) required to compensate for the decreased intensity remaining in the waveguide (blue) to keep the diffracted light constant (yellow). The diffraction efficiency shown in this figure is for the on-axis field for a thick hologram which can theoretically achieve 100\% DE reconstructed by the creation wavelength.

![Diagram showing the diffraction efficiency profile](image)

Figure 2.4. Longitudinal diffraction efficiency profile (red) of the redirection and extraction holograms according to the number of interactions with the hologram to compensate for the reduction of intensity inside the waveguide (blue) to keep the extracted intensity constant (yellow) [1].
2.2.3 Extraction Hologram

The extraction hologram was designed to receive the collimated beam from the redirection hologram and diffract the collimated beam towards the user. By out-coupling a collimated beam the image is located at infinity. The pupil was expanded by multiple extractions, and the uniformity of the extracted image intensity was guaranteed by varying diffraction efficiency across the hologram, as explained earlier in section 2.2.2.

2.3 Computer Simulation

The holographic waveguide HUD design was optimized using the optical simulation software Zemax Optic Studio and a coupled wave analysis program to calculate the angular and spectral dispersion of the holograms. Figure 2.5. shows the configuration and Figure 2.6. shows a ray tracing of the HUD where a point source is collimated, propagates throughout the waveguide, and is extracted toward an array of detectors.
Figure 2.5. Schematic of the HUD systems showing the three sections of holograms with modulated DE values to achieve pupil expansion in two dimensions [1].
Figure 2.6. Isometric view of our Zemax model showing point source reading beam propagating through the system and extracted normal to the waveguide surface. A color code was assigned to show each section the image undertakes: cyan, source to insertion hologram; blue, insertion hologram to redirection hologram; green, redirection hologram to extraction hologram; red, extracted light to detector [1].

A BK7 300 mm by 200 mm by 25.4 mm slab of glass was used as the waveguide with an index of refraction of 1.5195 at a wavelength of 532 nm.

The hologram lens feature was used in Zemax to simulate the HOE’s function. The 60 mm by 80 mm insertion hologram, with a focal length of 114 mm, redirects the beam as an edge-
lit hologram to satisfy TIR conditions at 60°. 10 mm from the insertion hologram, the redirection hologram at 60 mm by 180 mm was placed as a reflection hologram with three sections of varying reflectivity which simulated the varying diffraction efficiency. Its recording geometry allows incident light from the insertion hologram to be diffracted 90° at an angle of 52° to satisfy TIR conditions. 10 mm from the redirection hologram, the extraction hologram at 110 mm by 180 mm consists of two sections where one reflects 50% of the light while diffracting the other 50%, and the other section has a 100% efficiency diffracting all the remaining incident light.

The extracted light is directed toward an array of human eye pupil sized detectors (3 mm by 3 mm) spread across a 50 mm by 100 mm eye box, 114 mm away from the waveguide. These parameters yielded an expanded eye box with a FOV of 28° by 28°, as seen in Figure 2.7. This ray trace shows the geometrical limits of the system with ideal holograms of 100% DE capability and infinite bandwidth. A real hologram is analyzed using Kogelnik coupled wave analysis to supplement this ray trace later in this section.
Figure 2.7. Angular radiance of Zemax detector 114 mm behind extraction hologram on BK7 waveguide showing perceived image at infinity occupying a maximum FOV of 28° by 28° over the expanded eyebox. The perceived image brightness uniformity is preserved by spatially varying the diffraction efficiency of the redirection and extraction holograms [1].

The FOV depends on the distribution of angles that can propagate throughout the waveguide. Since the minimum angle is the critical angle, materials with a higher refractive index allow for a larger FOV. It was found that to achieve a 40° by 40° FOV, a refractive index of at least 1.8 should be used for the waveguide. However, these specialty glasses come at a higher cost and were unavailable for the recording of the demonstrator. Another aspect to large FOV with holograms is the angular and wavelength selectivity which will limit the FOV.

The Kogelnik coupled wave analysis [21] was used to supplement the Zemax model regarding the angular selectivity of the HOEs. This analysis showed that the diffraction
efficiency of the edge-lit insertion and redirection hologram have a limited acceptance angle for a monochromatic source. At the design wavelength of 532 nm, the full width half maximum system efficiency is only 0.5°. By using a polychromatic source, the angular selectivity of the hologram can be increased thanks to the superblaze (envelope of all the dispersion curves at various wavelengths) characteristic of the holograms, shown in blue in Figure 2.8. This demonstrates that the HUD would require a polychromatic image source to achieve a larger FOV.

Figure 2.8. Diffraction efficiency computation according to both incident angle in degrees and wavelength for the redirection hologram geometry, using the Bayfol HX200 material parameters (16 µm thickness). Angles shallower than 41.8° are not under TIR conditions [1].
2.4 Proof of Concept Demonstrator

A demonstrator was created after optimizing the system configuration using the optical simulation software Zemax and the coupled wave analysis.

The waveguide was made of Saint Gobain Diamant glass which is a low iron, highly transparent material with very little residual color compared to the more traditional soda–lime–silica float glass. The Diamant glass replaced BK7 from the simulation due to its exceptional optical transmission properties and similar refractive index experimentally determined to be 1.52. All the holograms were recorded using the Covestro Bayfol HX200 photopolymer.

2.4.1 Hologram Recording

The holograms were recorded from the interference of a doubled Nd YAG laser at 532 nm split into a reference and object beam. Using 18 mJ/cm² exposure dosage and a polarization orthogonal to the Bragg planes being recorded gave a maximum of 96.7% DE. The Bragg plane of a hologram is the orientation of a theoretical plane where max diffraction is obtained from a reconstruction beam for a given wavelength where the law of reflection and phase matching condition are satisfied [22]. The recording polarization affects the max DE obtainable [23]. Prism couplers were used to insert the beams at TIR inside the waveguide. Index matching was ensured using microscope objective immersion oil. We chose to make the insertion hologram 65 mm x 85 mm, redirection 65 mm by 160 mm, and extraction hologram 105 mm by 160 mm all spaced 10 mm apart in reflection geometry. Each recording setup is shown later in this section.

A polarization rotation was noticed in the diffracted light from the insertion hologram. Because of the sensitivity to polarization during the recording of the hologram, it was not possible to directly use the light diffracted by the insertion hologram to record the redirection
and extraction holograms. Instead, we record each hologram independently from each other, having neither object nor reference beams passing through any holograms.

To achieve a compact system and increase the image magnification capability, the insertion hologram should have the shortest focal length possible. To do so, we used the light expanded by a microscope objective (60×) as the object beam, while the reference beam is collimated and incident at 60° as seen in Figure 2.9. The polarization direction in this image is in and out of the page. Using this configuration, the object plane of the system is located at the focus of the microscope objective.

Figure 2.9. Recording geometry for the insertion hologram where the object beam is an expanding beam from a 60x microscope objective located 114 mm from the waveguide and the object beam is a collimated beam which propagates at an internal angle of 60° of the waveguide.
The redirection recording setup involved coupling 2 beams under TIR conditions using prisms. A reference beam is expanded from a spatial filter and collimated by a plano-convex lens. This hits a mirror to achieve the correct angle required in the hologram. A collimated object beam then enters the waveguide by 2 prisms stacked on one another. This setup is demonstrated in Figure 2.10

![Figure 2.10](image)

Figure 2.10. Ray trace for the recording setup for the redirection hologram. The reference beam shown in blue is directed downward while the object beam (not shown) enters the 2 stacked prisms in the direction into and out of the page.

The extraction hologram recording setup is shown in Figure 2.11. The reference beam is shown in red which is collimated and coupled by an index matched prism to the waveguide. The object beam is shown in blue which is collimated. In this setup, multiple interactions of the recording light are suppressed to produce high efficiency holograms.
Figure 2.11. Ray trace of the recording setup for the extraction hologram. The reference beam is shown in red and is coupled into the waveguide via index matched prisms. The object beam is shown in blue which involves a collimated beam.

To achieve the modulated DE required for the redirection and extraction pupil expansions, as discussed in section 2.2.2, the material was pre-exposed. The pre-exposure method starts the polymerization process in the photopolymer, effectively reducing the maximum DE capacity. The pre-exposure is done by illuminating the material with a single homogeneous beam before recording the interference pattern with both reference and object beam at normal recording power. A 5.5 mJ/cm² pre-exposure at 532 nm was found to reliably yield 50% DE. The material is non-uniformly pre-exposed to spatially alter the max efficiency the hologram across its surface. During recording of the holograms, pre-exposure was used to illuminate the areas of the hologram which required less DE. Afterwards, the entire hologram was recorded and cured resulting in non-uniform DE across the hologram surface.
2.4.2 System Testing

We used a 3M portable projector model MP220 as a polychromatic light source for the HUD. However, due to the spectral selectivity of the holograms only the green portion of the spectrum, centered on 532 nm, is efficiently transmitted through the system. Nonetheless, the dispersion allows wavelengths of ± 20 nm to propagate at different angles, with the smaller angles being red-shifted (532+20 nm) and larger angles being blue-shifted (532-20 nm).

This spectral shift has an important implication on the geometry of the object plane. The focal distance of a diffraction lens depends on the wavelength, being shorter for larger wavelengths. If the object plane is strictly parallel to the waveguide, the blue-shifted and red-shifted parts of the image are out of focus and do not overlap correctly with the central green image, yielding image distortion and splitting. To compensate for this effect, the object plane was tilted 7° in the vertical direction and 15° in the horizontal direction, as seen in Figure 2.12. These values were found experimentally.
Figure 2.12. Object plane of the HUD showing the required tip and tilt with respect to waveguide surface to compensate for polychromatic dispersion. The object plane for the HUD is the image plane produced by the projector which is located 114 mm from the insertion hologram and centered along the optical axis. For this image, the object formed by the projector overfills the HUD transmittable FOV [1].

The spatial resolution of the HUD was observed using a standard US Airforce 1951 Test Target. The target was placed at the object plane and illuminated with a polychromatic source. The extracted image has a maximum insertion resolution of 12.7 lines per mm in the central field.
and an outcoupled image of 29 cycles/deg as it could be observed from Figure 2.13.

Image blurriness along the periphery is attributed to secondary aberrations, such as the need for a non-planar object plane, and the flatness of the holographic material.

Figure 2.13. Image of a US Air Force Resolution Target through the HUD showing a resolution of 12.7 lp/mm in the central field of view in object space and 29 cycles/mm in image space. Fig a. is outcoupled image while fig b. is enlarged [1].

Figure 2.14. shows the respective size of the injected image (right) and the extracted image (left) demonstrating the infinite image magnification by the system. As seen, a small projected source is magnified decreasing the required projector size from traditional HUD systems. The outcoupled image has a horizontal FOV of 6.6°.

Figure 2.15. and Figure 2.16. show pictures of the HUD taken with a digital single lens reflex (DSLR) camera with a background image of a runway located in the far field. Figure 2.15.
was taken with the camera focused on the waveguide plane, showing that both the far field image and the symbology projected through the HUD system are out of focus. In Figure 2.16, the camera is focused at infinity and the symbology projected by the HUD overlays the image located in the far field. This demonstrates that the user does not have to accommodate to see the image.

Figure 2.14. Picture of the prototype HUD system using a high f-number camera objective resulting in large depth of view for object and image planes in focus. Notice the small insertion image which is magnified as the out-coupled image. The inserted object is located on an object
plane in front of the insertion hologram while the projected virtual image is located at infinity resulting in infinite magnification with a size of 6.6° [1].

Figure 2.15. Picture of the HUD system taken with a DSLR camera when focused at the location of the waveguide. The background runway is displayed on a monitor located in the far field, the symbology (green) is projected at infinity through the HUD system [1].
Figure 2.16. Picture of the HUD system taken with a DSLR camera when focused at infinity. The background runway is displayed on a monitor located in the far field, the symbology (green) is projected at infinity through the HUD system [1].

The FOV was determined by imaging the output light from the extraction hologram with a lens and measuring the size of the image relative to the focal length. A monochromatic light source produced a FOV of only 8.1° by 6.6° found experimentally due to the angular selectivity of the holograms as discussed in section 2.3. However, using a polychromatic source, the FOV is extended to 24.1° by 12.6°, in the horizontal and vertical directions, respectively, found experimentally.

2.5 Conclusion

A HUD using HOEs on a waveguide can effectively offer a solution to the size limitations of traditional HUDs. Our prototype demonstrates a 24° by 12.6° FOV in the horizontal and vertical directions, respectively, over an 80 mm by 110 mm eye box with a max insertion
resolution of 12.7 lines/mm. The expanded eye box was due to the 1.9× by 1.6× horizontal and vertical pupil expansion, respectively. Image magnification and image projection in the far field are a result of the insertion hologram’s optical power. HOEs had to be recorded individually due to polarization rotation effects in the diffracted light of edge-lit holograms. The polarization change has not been thoroughly examined but was determined to be spatially random across the insertion hologram and may be a result of the combination of in-coupling and lensing effect recorded into the insertion hologram. The chromatic dispersion requires a tilted object plane to ensure the correct focal distance. The prototype still shows some aberration in the projected image, especially in the peripheral field of view. The simulation does not reproduce these aberrations, leading us to believe that they are due to the imperfections of the hologram, which include trapped air bubbles under the material, and hazing which results from the recording of scattering into the hologram, and the object plane. The object plane may be a curved asphere according to the focal length shift calculated from Bragg’s law of diffraction.

The difference between the simulated FOV of 28° by 28° in Zemax and experimental FOV of 24° by 12.6° is due to Zemax’s ability to calculate diffractive optics properties. It does not account for diffraction efficiency according to angular acceptance or wavelength acceptance. Zemax provided a geometrical limit on what will propagate through the system. Kogelnik coupled wave analysis showed that each hologram has varying diffraction efficiency according to both angular and wavelength acceptance. The summation of the DEs result in a fall off along the edges yielding low image brightness along the edges and ultimately FOV limitation in the demonstrator.

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Chapter 3
Examining Image Artifacts Due to Depth of Field in Holographic Pupil Replication Waveguide Systems

This chapter examines the artifact of image duplication from insertion of objects at varying depths producing images of varying depths of field through a pupil replicating system based on holographic optical elements on a planar waveguide.

3.1 Background

Research has been conducted to reduce the form factor of HUD and AR systems where one such solution is waveguide pupil replication. Eyebox expansion by pupil replication has become an important advancement which can also reduce the footprint of HUD and NED systems while increasing the field of view. This is particularly advantageous in NED systems where a small form factor is crucial and generally results in a small exit pupil in traditional systems [24].

The eyebox is defined as the 3-dimensional volume over which a user can move their eyes and see the entire projected image. Field of view is defined as the angular size a projected image encompasses of a user’s visual system. The footprint of the system can include the waveguide coupling optics and the projector system. The exit pupil of a typical NED should be at least 15 mm in diameter to allow for the waveguide to shift while in use and allow for the user to be undisturbed
by the movement as the image is still present as well as to compensate for the differences in interpupillary distance among the human population [25]. Pupil replication can expand the small exit pupil produced by a light engine to fill the required exit pupil size. The concept of pupil duplication using a waveguide extracts recirculated light multiple times increasing the pupil can be seen in Figure 3.1. This can be applied to both the vertical and horizontal directions for a 2-dimensional pupil expansion. In order for the extracted light to have a uniform brightness, the extraction efficiency should vary along the number of extractions [1]. To avoid aberration in the final image, stringent tolerances are imposed on surface defects on the waveguide since these surface errors are being compiled by the multiple interactions through total internal reflection [26].

A holographic waveguide system consists of an insertion hologram and an extraction hologram. The insertion hologram couples image bearing light into a planar waveguide. This light propagates through the waveguide until it interacts with the extraction hologram. The diffraction efficiency of the extraction hologram should vary along the propagation path of the light, so the same amount of light is directed toward the viewer regardless of its position in the entire extraction region. The varying diffraction efficiency preserves the image brightness across the eyebox.

For 2D pupil expansion, a redirection hologram is located between the insertion and the extraction hologram. The purpose of the redirection hologram is to expand the pupil in one dimension while keeping the light inside the waveguide by redirection at 90 degrees. In this case, the light that was initially traveling across the width of the waveguide is now traveling along its length, and the extraction hologram expands the pupil in the other dimension.
Figure 3.1. Concept of 1 dimensional pupil replication where light is recirculated within the waveguide to be extracted more than once to increase the area the image can be seen [2].

For a true immersion experience, the psychological and physiological visual cues must be satisfied [27]. A display should produce the physiological cues such as accommodation, vergence, motion parallax and occlusion. This involves presenting a virtual projected image into the user’s FOV to simulate an object at a certain distance from the user’s perspective. If these are not satisfied, it can lead to the accommodation-vergence conflict resulting in the user being disoriented while using the display [11, 12]. A method would be to display holograms to the users which satisfy all visual cues [11, 28]. Other methods could be to use a mechanically shifting object plane or a pupil relayed deformable mirror to temporally multiplex image planes [29]. However, when the focal distance of the image, or the hologram, that is injected into the waveguide changes,
artifacts such as image replication appears. In this chapter, we examine this artifact according to the image distance using both a Zemax ray tracing model and a lab demonstrator. We propose a solution where the image can be projected at discrete locations, allowing to restore both vergence and accommodation cues.

3.2 Optical System

The optical system we are investigating is schematically represented in Figure 3.1. Waveguide pupil replication is achieved using holograms laminated to a flat glass waveguide. An edge lit hologram diffracts light at an angle such that it satisfies the total internal reflection condition. The insertion hologram receives incident image bearing light and couples the image by redirecting it to propagate internal of the waveguide. The mean angle of propagation takes the halfway point between the critical angle for TIR and when the angle is so extreme that it misses the extraction hologram demonstrated in Figure 3.2. The extraction hologram outcouples light from the waveguide and directs it toward the user. The extraction hologram has segmented diffraction efficiency to extract a percentage of the light as the light propagates through the waveguide. This allows for a uniform brightness of the image as the user moves across the expanded pupil.
Figure 3.2. Schematic showing field of view limits within the waveguide and the position of the central angle compared to the FOV limits.

A waveguide has its insertion and extraction holograms designed to couple the image at a certain prescribed image distance. The insertion hologram collimates the rays entering the waveguide such that the image does not suffer any (de)magnification when propagating inside the waveguide. If not so, each extraction generates an image of different size which produce an artifact. The extraction hologram, in addition to extracting the light from the waveguide, defines the image distance of the waveguide by the focal length of the hologram. In the case of a simple grating, the image is located at infinity. To locate the image at a different distance, the extraction hologram should be given some negative optical power.

As the image distance deviates from the prescribed distance, image doubling is observed across the expanded eyebox. The angle between the doubled images were measured at the deviated
distances in a ray tracing software (Zemax) and a demonstrator of a holographic waveguide display with pupil replication.

### 3.3 Computer Simulation

The optical ray tracing program (Zemax, Optic Studio) was used to model the holographic waveguide display in non-sequential mode. A 19 mm thick N-BK7 waveguide was modeled with 3 hologram segments. A square 50 mm x 50 mm insertion hologram and 2 extraction holograms. The extraction hologram consisted of two segments identical to the insertion hologram dimensions making a total size of 100 mm x 50 mm for a 2x pupil expansion. The insertion and extraction holograms were designed to propagate collimated incident light throughout the system and were modeled with Zemax's hologram lens feature. A 0 diopter waveguide and a 2 diopter waveguide model were developed with the optical parameters for the holograms listed in Table 3.1, which extract the image to project it at infinity and 500 mm from the extraction hologram, respectively. The recording geometry is given for the reference and object beams along with the recording wavelength, index of refraction and diffraction efficiency of the holograms.
Table 3.1. The hologram parameters for the waveguide display systems modeled in Zemax's non-sequential mode [2].

<table>
<thead>
<tr>
<th>Hologram Parameters</th>
<th>Waveguide</th>
<th>0 Diopter</th>
<th>2 Diopter</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>1st Ext</td>
<td>2nd Ext</td>
</tr>
<tr>
<td>Hologram</td>
<td>Insert</td>
<td>Reflect</td>
<td>Reflect</td>
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<tr>
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<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Z&lt;sub&gt;ref&lt;/sub&gt; (mm)</td>
<td>1E8</td>
<td>1E8</td>
<td>1E8</td>
</tr>
<tr>
<td>X&lt;sub&gt;obj&lt;/sub&gt; (mm)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Y&lt;sub&gt;obj&lt;/sub&gt; (mm)</td>
<td>0</td>
<td>-1.35E8</td>
<td>-1.35E8</td>
</tr>
<tr>
<td>Z&lt;sub&gt;obj&lt;/sub&gt; (mm)</td>
<td>1E8</td>
<td>-1E8</td>
<td>-1E8</td>
</tr>
<tr>
<td>λ&lt;sub&gt;rec&lt;/sub&gt;/n (um)</td>
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<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>n</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
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<tr>
<td>Efficiency %</td>
<td>100</td>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>

Point source objects were input into the system at different distances and an imaging system was set up after the extraction hologram to find the virtual image distance as well as the angle of image doubling. The imaging system consisted of a 100 mm paraxial lens and a translatable detector plane to find the best focus which the distance between the doubled images could be measured. The distance between the doubled images and the image distance from the paraxial lens to the detector were used to calculate the angle between the doubled images.
A waveguide designed to incouple and outcouple collimated light designed in Zemax is shown in Figure 3.3. A point source object is located 250 mm in front of the insertion hologram. The extraction holograms outcouple the light which produce a virtual object located 250 mm plus the internal propagation path length through the waveguide. Rays have been back traced to show the virtual image which each extraction hologram segment creates. Figure 3.4. shows the 2 virtual images created for an on axis point source 250 mm from the insertion hologram. The rays differ for each image from the pupil expansion which can both be viewed as a doubled image if the imaging system is within the indicated region of doubled image or receives light from both extractions. The doubled image differs by angle and projected image distance. The difference in projected image distance is an error in magnification across the pupil in both horizontal and vertical directions.

The projected images are shown in Figure 3.5. with the object distances both matching and straying from the designed waveguide parameter where the waveguide parameter is the focal length of the extraction hologram. This is the outcoupled image distance which occurs when the internally propagating reference beam is collimated. A paraxial lens collimates the 10 mm x 10 mm object to project it at infinity. A 2nd paraxial lens is used to induce 0.323 D of optical power to project the object at a different distance. With the image at infinity, there is no image doubling while the image at 3.4 m causes an image doubling of 0.86° seen as the horizontal direction.
Figure 3.3. Zemax layout of the pupil replicating waveguide designed for imaging at infinity. Dark blue is the waveguide, dark yellow is the insertion hologram, cyan is the 1st extraction hologram segment, magenta is the 2nd extraction hologram segment. The rays are color coded green for upper portion of the insertion hologram pupil, yellow for the center and red for the bottom. The rays from a single point enter the insertion hologram and produce virtual points which change in projected distance [2].
Figure 3.4. Zemax layout of the pupil replicating waveguide designed for image at infinity. The object is at 250 mm producing 2 virtual images from pupil replication. The virtual images form a region of overlap where an imaging system can view both images simultaneously resulting in angularly separated image doubling [2].
Figure 3.5. The detector in a Zemax ray trace is shown here. a) The projected image matches the designed waveguide parameter and is free from artifacts. b) There is a mismatch between the projected image distance and the waveguide parameter causing 0.86° of difference in line of sight between the doubled image [2].

The image doubling occurs immediately after the extraction of the image and is most visible at the location where the image is extracted by a different segment, or when a different portion of the image is extracted by a same location of the hologram. Every ray that enters the insertion hologram has their angle preserved as they propagate through the waveguide and the replicated rays are extracted parallel to each other. An undisturbed image can be seen if the entire FOV of the image is only within a single extraction hologram segment. As the detector is swept across the eyepiece, image doubling will be seen until the next single extraction hologram segment projects the entire FOV.
The Zemax model was altered to have a designed input and output which allows for a virtual image to be displayed at a distance closer than infinity. In Figure 3.6, a layout is shown of a system which is designed for an object and image at 500 mm distance. A waveguide designed for a certain distance implies that the internal propagating beam within the waveguide is near collimated, but the extraction hologram acts as a negative lens. This results in no image doubling in between replicated pupils as both replication segments produce an image at the same location seen in Figure 3.7(a). However, when the image is projected at another distance than the prescribed 500 mm, image doubling is present seen in Figure 3.7(b). This difference in projected image depth from 500 mm to 600 mm caused 1.0° of image doubling. The object size was 40 mm x 40 mm for Figure 3.7. and to preserve the virtual image size, a paraxial lens was used before the insertion hologram to add 0.33 D of optical power to project the object at a different distance.

Figure 3.6. Layout of a Zemax model of a waveguide designed to couple light at an object distance of 500 mm and project it virtually at 500 mm. Back tracing the rays shows that the eyebox creates a single virtual image point [2].
For larger FOV images, the image doubling will only occur on the sections of the image which are outcoupled by different extraction holograms. This results in no image duplication far outside the area where the replicated pupils exist.

![Image at 0.5 m](image1)

![Image at 0.6 m](image2)

Figure 3.7. a) The projected image is matching the designed waveguide parameter and has no artifacts. b) The projected image does not match the waveguide parameter and has 1.0° of difference between the doubled image [2].

### 3.4 Proof of Concept Demonstrator

Three holograms were recorded on a 19 mm thick glass waveguide using 16 µm Covestro Bayfol photopolymer [30]. The insertion hologram is a square with dimensions of 50 mm x 50 mm. The extraction hologram total size is 50 mm x 100 mm. There is no spacing between the hologram segments. A grating period of 0.298 µm is recorded into 16 µm thick photopolymer material to achieve an edge lit hologram using a frequency doubled YAG Coherent laser at 532 nm.
The insertion hologram was recorded using a coupling prism for the collimated object beam and a collimated normally incident beam as the reference beam. The angle of the object beam was set at 53.5° which is the median angle between the total internal reflection angle and the angle at which internally propagating light would miss the extraction holograms. To achieve this recording angle, a coupling prism was index matched to the waveguide during the recording process of the insertion hologram seen in Figure 3.8.

![Figure 3.8. Recording geometry for the insertion hologram. The green light shows the object beam while the red shows the reference beam which interferes at the hologram.](image)

The extraction hologram consisted of 2 segments which expanded the pupil in 1 dimension by 2x. The extraction holograms were recorded using a collimated single large beam which served as the object beam. The reference beam was formed from the resulting collimated diffracted light from the insertion hologram. The recording setup can be seen in Figure 3.9. Extraction hologram (blue) recording setup where incident collimated light (light green) is the object beam and
diffracted light (dark green) from the insertion hologram (red) is the reference beam. The layout of the holograms on the waveguide can be seen in Figure 3.10.

![Diagram showing hologram layout](image)

Figure 3.9. Extraction hologram (blue) recording setup where incident collimated light (light green) is the object beam and diffracted light (dark green) from the insertion hologram (red) is the reference beam.

![Demonstrator with holograms](image)

Figure 3.10. Demonstrator showing 3 segments of coupling holograms named the insertion and 1st and 2nd extraction holograms. Each hologram is laminated to an N-BK7 waveguide [2].
3.5 Results

The image doubling was captured by ray tracing software by varying the object distance and recording the pixel shift between the two objects created. The image doubling was captured in the demonstrator by moving the object plane of the projector to produce virtually projected images at different distances. The angular difference in the images were measured against the virtually projected image distance using the imaging equation which relates object distance, image distance and focal length. The object used was a 1951 Air Force Resolution Target (ARFT). Figure 3.11 shows similar amounts of image doubling resulting from the demonstrator and the simulation of group 3 of the AFRT.

Figure 3.11. Left image a) is contrast enhanced and shows image doubling of an Air Force Resolution Target in the demonstrator captured with a digital single lens reflex camera while the right image b) shows image doubling of a simulated Air Force Resolution Target in the Zemax ray tracing model [2].
An angle was calculated from the difference in the doubled image to find a relationship between the object distance and the image doubling denoted $\alpha$. This led to a theoretical equation describing the relationship seen in Eq. 3.1. Equation 3.2 describes the effective size of the pupil from pupil replication.

$$\alpha = 2 \arctan \left( \frac{pupil}{-2zi} \right),$$

$$pupil = L(N - 1),$$

where $z_i$ is the virtually projected image distance in millimeters which is negatively signed in accordance to the sign convention of a Cartesian coordinate system. $L$ is the insertion hologram size in millimeters in 1-dimension multiplied by the number of extraction hologram segments $N$ where the term $N$ is rounded up to the nearest integer.

The user’s eye accommodation is the variable $\varphi$ which is in units of diopters to see the object at the projected distance is shown in Eq. 3.3. The eye accommodation is defined as the inverse of the negative image distance with a conversion factor from inverse millimeter to diopter. A linear correlation was realized when using the user’s eye accommodation as the independent variable instead of the virtual image distance.

$$\alpha = 2 \arctan \left( \frac{pupil \cdot \varphi}{2 \cdot 1000} \right).$$

The angle found in the demonstrator and the Zemax simulation are compared to the theoretical equation in Figure 3.12. The parameters are that the pupil is 50 mm, and the image distance range was from -3.4 m to $-\infty$. It is seen that as the image distance approaches infinity the image doubling approaches zero. The point where the image is at infinity and the image doubling is 0 was intentionally left out to be able to see the trend at lesser image distances.
Figure 3.12. Plot showing the angle between the doubled images due adjusting the object distance to produce a virtually projected image at assorted distances [2].

It is seen that upon analysis of a waveguide which was designed to produce a virtual image other than at infinity, the optical path length from the extraction pupil becomes a factor in the image doubling as well as the designed image distance of the waveguide display. This relationship is shown in Eq. 3.4,

\[ \alpha = 2 \arctan \left( \frac{1}{z_w} + \frac{1}{z_l} \right) \frac{pupil}{2} \left( 1 - \frac{t}{z_w} \right). \]  

(3.4)
The variable $z_w$ is the designed projected distance of the waveguide and extraction holograms in millimeters. It is negative as it is a virtually projected distance. The variable $t$ is the optical path length from the extraction hologram to the user’s pupil in millimeters.

Equation 3.4 can be rearranged to find the depth range that can propagate through a waveguide by setting the angle of image doubling to 1 arcmin. At this angle, any image doubling would be unnoticeable to the user as this is the limit of the visual acuity of a standard human observer [31].

A waveguide display used to outcouple a virtual image at 0.5 m was simulated in Zemax. The image doubling as a function of image distance was observed by varying the object distance from the waveguide insertion hologram and viewing the produced image after the extraction holograms. This was plotted against the relationship shown in Eq. 3.5 in Figure 3.13. To demonstrate this effect in the lab, an 0.5 m negative lens was placed after the extraction hologram. The parameters considered were a pupil of 50 mm, an optical path length of 28.9 mm, $z_w$ of -500 mm and a $z_i$ range from -433 mm to $-\infty$ mm. The data point at infinity is not shown in the plot.
3.6 Discussion

The root of the image doubling artifact comes from the fact that the different rays originating from a single point of the image are not propagating collimated inside the waveguide. During the extraction, the rays extracted first are forming a different image from the image formed from the replicated rays extracted later on during the pupil expansion process. The cause of the image doubling when the image is projected at a distance different from which the waveguide is intended for can be seen in Figure 3.4. Zemax layout of the pupil replicating waveguide designed for image

Figure 3.13. Plot showing the angle between the doubled images due to adjusting the object distance to produce a virtually projected image at assorted distances for a waveguide display designed to project an image at 0.5 m [2].
at infinity. The object is at 250 mm producing 2 virtual images from pupil replication. The virtual images form a region of overlap where an imaging system can view both images simultaneously resulting in angularly separated image doubling [2]. Each replicated pupil creates its own image of the original object. If the object is a centered point source, each replicated pupil will create a centered point source relative to each replicated pupil. When viewing the extracted image, a pair of point sources can be seen separated by an angle based on the position of these point sources relative to each other.

Each segment of the extraction hologram produces its own virtual object. If the detection system is placed directly behind one of the segments of the extraction holograms, a single point is seen from the object. If the detection system is placed in between the segments of the extraction holograms, light rays enter the detection system from both segments and are viewed as two offset points in the direction of pupil replication. The angular difference between these points are causing image doubling.

Equation 3.4 can be rearranged to find the range of depth that can be put into a waveguide by solving for the variable $z_i$ and setting the angle between the doubled images to 1 arcmin to be unnoticeable to the user based on visual acuity. The difference between the image distances for positive and negative values of 1 arcmin can be used to find the depth range and this can be approximated by Eq. 3.5,

$$\Delta z \approx 2 \left\{ \left( \frac{1}{z_w} - \frac{2}{pupil} \right) \cdot \frac{\tan \left( \frac{\alpha}{2} \right)}{1 - \frac{t}{z_w}} \right\}^{-1} - z_w \right\}. \quad (3.5)$$

The depth range relationship can be used to find the depth of field which a waveguide display can transmit without inducing noticeable image doubling across the expanded eyebox by
pupil replication. Figure 3.14 shows the depth range which a waveguide can transmit according to its extraction hologram's focal length. As the extraction hologram's focal length decreases, the depth range decreases. As the pupil size is decreased, a larger depth range can be transmitted before noticeable image doubling occurs. A shorter optical path length from the extraction holograms to the user’s entrance pupil will also increase the depth range.

Figure 3.14. Log scaled plot showing the image depth range that can be transmitted by a waveguide display with pupil replication according to the designed image distance of the waveguide display. The difference between effective pupil sizes is shown. These are related to the depth perception of the standard observer based on binocular disparity [2].
As it can be seen from Figure 3.14, the depth range is extremely limited: 1/100 of the projected distance for a 50 mm pupil and 1/50 for a 25 mm pupil. These ranges can be compared to the standard observer's depth perception based on binocular disparity. According to [32], the angular acuity of a person is 20 arc seconds for normal vision. The approximation for angular disparity based on geometry given by [33] can be rearranged to solve for the depth between 2 objects shown in Eq. 3.6. The relation between viewing distance and depth range for the standard observer is plotted against the depth range of an artifact minimized pupil replicating waveguide system. The variables are defined as that \( \Delta d \) is the depth range, \( D \) is the image distance, \( I \) is the interpupillary distance and \( \delta \) is the angular acuity. It can be seen that the standard observer may be able to view depth information from a single pupil replicating waveguide.

\[ \Delta d \approx \frac{D^2 \delta}{I - D \delta}. \] (3.6)

A possible way to overcome the limitation of depth range within a single waveguide display is to use multiple waveguides in a multi-focal configuration. A Zemax simulation was constructed with two waveguides, one designed for projecting the image at -2.1 m, and the other projecting the image at infinity. For this model, the insertion holograms between waveguides were spatially separated to avoid cross talk while the extraction holograms were overlaid for the images to appear to be in the same field of view. Since the insertion holograms are spatially separated, multiple light engines are required to produce each depth plane. Alternatively, a single light engine can be used with different sections of the image injected by the different input holograms. The output images are shown in Figure 3.15 over a 2x expanded pupil. Notice there is no image doubling with 2 distinct projected image distances. Using this waveguide multiplexing technique,
multiple images can be projected at different distances respecting both the accommodation and the vergence optical cues for the viewer. Considering the waveguide use in HUD and AR glasses can be as thin as a fraction of a millimeter, this technique does not make the combiner too bulky or heavy. For a sufficiently large depth of field from 0.33 m to infinity, 6 waveguides can be used [34].

For the sake of this example, we have chosen a set of parameters for the waveguide where the image doubling phenomenon is quite distinct and can be clearly visualized. However, it has to be kept in mind that for other parameters such as insertion angle and waveguide thickness, the image doubling phenomena can be more acute and visually complex.

Figure 3.15. Zemax Simulated images with 2 depth sceneries overlaid on another. Left is University of Arizona symbol imaged at 2.1 m and the right is the College of Optical Sciences logo imaged at infinity [2].
3.7 Conclusion

Image doubling is observed in pupil replicating holographic waveguide displays when the internal propagation within the waveguide is not collimated. The limit of image splitting is set by the user’s ability to detect an angular difference which is set by the human visual acuity. We showed that this tolerance is extremely small, and the image depth range can only be a small fraction of the projection distance (1/50). Propagation of larger depth ranges will result in image doubling across an expanded pupil.

The depth range that can propagate through a pupil replicating waveguide is limited by the designed waveguide projected image, the pupil size, the optical path length from the extraction hologram to the user’s detection system and the tolerable angular displacement between doubled images.

To have a mixed reality experience, multiple waveguides, where each is for a different image depth, should be used if pupil replication is desired.

Chapter 4
Holographic Curved Waveguide Combiner for HUD/AR

This chapter presents a method for creating a curved combiner for head up display and augmented reality applications with pupil replication based on holographic optical elements on a curved waveguide.

4.1 Background

Holographic waveguides for augmented reality and mixed reality glasses have shown significant advantages compared to other types of combiners. This is because the waveguide approach can, thanks to pupil replication, increase the eye box without compromising the field of view. However, holographic waveguides have so far been limited to flat substrates, that could be difficult to implement in some systems and lack aesthetic appeal.

In near to eye display combiner need to be lightweight, have a small footprint, large field of view and easily integrated for social acceptability [13, 14]. Some examples of combiners include semitransparent mirrors, dichroic mirrors, and holograms. A semitransparent mirror as a combiner generally suffers from small field of view since the last optical component is far from the viewer. On the other hand, a combiner based on holographic optical elements can act as the last element and potentially have a larger FOV making them an excellent candidate for head up display and AR systems.
HOEs can be fabricated to diffract light which satisfies both its angular and wavelength requirements. They can appear clear with little ghosting effects and propagate out of view images into the eye making them excellent candidates for see through displays. Their ability to condense complicated optical systems into a thin hologram layer can lead to lightweight and small footprint systems.

In NED systems, the encompassed volume or footprint is an important property to manage. The footprint may include the projection optics and the combiner system. The projection optics create the FOV and pupil of a system. Using a pupil replicating combiner, a small projection system can be used leading to an overall smaller system footprint [1, 2]. The advantage of pupil replication is that it decouples the eyebox size from the field of view [26]. This allows for the use of small form factor projection optics as an input source to the display. Pupil replication through HOEs on a waveguide involve an insertion hologram which propagates light at total internal reflection conditions to reach an extraction hologram which outcouples portion of the light when the rest is recirculated many times to replicate the input pupil.

Pupil replication has traditionally been limited to flat waveguides. However, flat waveguides have poor integration into spaces and lack aesthetic appeal. These may be reasons for the lack of public interest in currently available AR systems. The benefits of a curved waveguide display are its ease of integration and better conformity to the public's social standards. An example for AR would be if a person would rather wear a pair of glasses with flat substrates or if they would wear an aggressive looking device with curved substrates such as sunglasses. Another benefit may be larger possible FOV achievable as the waveguide wraps around the user [35]. In the case of HUD, a curve waveguide can also be integrated directly into a curved windshield instead of standing in front of it.
4.2 System Design

The curved combiner consists of a cylindrically curved waveguide, an insertion HOE, and an extraction HOE. The HOEs are placed directly onto the waveguide and allow for coupling and extraction of light over an expanded pupil to act as a combiner display.

The waveguide shape is important for proper propagation. A waveguide shape which preserves thickness is best suited for a curved waveguide. This shape is when the outer and inner radius of curvatures are concentric. It is important to note that this shape induces some residual power after each TIR bounce leading to aberrations after long propagations through waveguides with relatively large thicknesses compared to radius of curvature. This happens from the radius of curvature being different between the 2 surfaces. Modeling has shown that a waveguide with the same radius of curvature, but radially outward varying thickness produces undesirable aberrations beyond which a uniform thickness waveguide produces.

The insertion hologram couples the light into the waveguide as well as applying the appropriate correction to the light. The insertion hologram is recorded such that it allows the internally propagating ray bundle to remain close to constant after each TIR bounce. A steeper or shallower center insertion angle will cause the scaling factor to be different. The thickness of the substrate and the size of the insertion hologram are dependent on each other. A thicker substrate allows for a larger insertion hologram. The equation, \( \tan(\Theta) = \frac{x}{2t} \), relates the angle used for propagation (\( \Theta \)) and the size of the insertion hologram (x) and the thickness of the substrate or waveguide (t). The size of the insertion hologram is the initial pupil of the system and should match the exit pupil of the projector for efficient throughput. If no expansion is used, then the pupil is virtual to the viewer and the entire field of view of the image cannot be seen. Only parts may be seen if the viewer moves their eye across the entire eye box.
When incident collimated light reflects off a curved mirror the focal distance of the on-axis field is \( r/2 \) in both sagittal and tangential directions where \( r \) is the radius of curvature of the mirror. When the field is increased to 54°, the sagittal rays still focus at \( r/2 \) but the tangential rays focus now at \( r/6 \). An important concept in previous waveguide head up display methods was that the light must propagate through the waveguide collimated so that the ray bundle does not expand or contract with distance [2]. This allowed for the extracted image to appear the same size across the eyebox. This concept applies to the curved waveguide as well where the image must stay the same size across the eye box. This cannot be accomplished with collimating the light but must be a constant astigmatic focusing and expanding ray bundle. The amount of focusing needed is dependent on the radius of curvature of the waveguide and the internal propagation angle. The focused light will be astigmatic where the sagittal rays must focus at a distance of \( f_s = r \) and the tangential rays must focus at a distance of \( f_t = r/3 \). At \( r/3 \), the 1:1 conjugate is satisfied for the off-axis rays. When the rays interact with the inner portion of the waveguide, they will see a negatively curved mirrored surface which will expand the ray bundles appropriately to allow for an overall unchanging image propagation method.

To propagate light internally of a curved waveguide, the light must undergo a balancing act between expanding and focusing as it interacts with the top and bottom surfaces through TIR. The summation of this through the waveguide allows for the extraction holograms to outcouple the light with little aberration. The main aberration the light undergoes as it TIRs in a 1D curved waveguide is astigmatism. At the centered angle of the on-axis rays, the rays must interact with the next surface as if it were a 1:1 imaging conjugate. For a curved mirror with a ray bundle incident angle of 54 degrees, the focus of the sagittal rays is located at a distance of approximately \( 0.3R \) where \( R \) is the radius of curvature. Therefore, the insertion hologram must have astigmatic
power where the sagittal rays focus at this 1:1 conjugate location. This is demonstrated in Figure 4.1.

The extraction hologram is segmented where each hologram is created with different geometry due to the waveguide curvature. This is to ensure that each section of the extraction hologram outcouples the light parallel across the expanded pupil. Each extraction hologram compensates for the residual optical power allowing for the outcoupled image to be viewed with minimal aberration. The extraction hologram segments should have varying diffraction efficiency to provide uniform illumination to the viewer across the expanded eyebox.

Figure 4.1. Insertion hologram geometric correction showing the sagittal focus induced in green and the resulting virtual focus from the TIR off the waveguide surface in red [3].
4.3 Computer Simulation

An optical model was created in Optic Studio Zemax to define the parameters for curved waveguide propagation. Figure 4.2(a) shows the layout of the system where an object beam is collimated and coupled into the waveguide at TIR conditions using a single HOE. After propagation internally in the waveguide for about 20 mm, the light interacts with the extraction HOEs where each section of the hologram has a varying efficiency to outcouple a constant luminance across the eyebox.

Shown in Figure 4.2(b) shows the ray tracing for a cylindrically curved waveguide (1D curvature) with an outer radius of curvature of 171.45 mm, thickness of 3.175 mm and an inner radius of curvature of 168.275 mm. The insertion hologram is a 9 mm x 9 mm square. The extraction hologram consists of 3 segments with a total size of 9 mm x 27 mm. The model is color coded where the black rays make up the projector, the green rays represent the internally propagating rays that are extracted at the 1st segment. The blue shows the rays which are not outcoupled at the 1st segment and continue to be outcoupled at the 2nd segment. The red rays show the 3rd segment extraction.
Figure 4.2. Left figure is the top view of a 1-dimensional pupil expansion through a 1 dimensionally curved waveguide. The black rays show from the object to its collimating lens. The green rays represent the internally propagating light towards the 1st extraction hologram segment diffracted from the insertion hologram located on the outer surface of the waveguide. The blue rays represent 2nd pupil expansion and the red show the 3rd expansion. The right image is a 3D layout showing the projection optics, the curved waveguide, and each hologram section [3].

The insertion hologram has added power of 8.06 D in the sagittal direction as well as the power introduced from being a curved surface with radius of curvature of 171.45 mm (2.879 D) and redirecting the light to propagate at a central angle of 54.6°. This angle can be varied slightly but should remain close to this value as it is between the angle for which the light does not TIR or misses the extraction holograms. In our simulation, the materials had an index of 1.5, as index changes, the insertion angle should be adjusted.

The light then interacts with the inner and outer surface of the waveguide which are opposite in power. This implies that the astigmatism that each surface generates on the wavefront
are of opposite sign. This allows for each field to propagation with minimal change in the ray bundle. The field of view is set by the index of refraction of the waveguide which allows for greater angular ranges as index of refraction is increased. Light is outcoupled if the angle of light does not satisfy TIR conditions or misses the extraction hologram at the FOV extremes.

The extraction hologram corrects any residual power and extracts the light out of the waveguide. The 1st extraction hologram accepts the focusing light from the reflection of the outer surface and outcouples 33% of the light and focuses the light at a focal distance equal to the power of the curvature of the inner side of the waveguide. The inner curved surface will then collimate the light for the viewer to see in the far field. The remaining light continues bouncing and is extracted in the same manner by the remaining extraction holograms except for an angular difference. The extraction angle must be changed to compensate for the extraction holograms not being normal to the same plane as each other. The angle is equal to the angle change between the centers of each hologram when referenced to the center of curvature of the waveguide. The residual aberration could be described as the difference in aberration from the replicated pupils across the expanded pupil which leads to focus errors and image duplication.

In order to compare the image quality with or without correction in the insertion HOE, the added power was removed in the ray trace model. The comparison between the outcoupled images across the eyebox can be seen in Figure 4.3. On the left panel, the uncorrected insertion hologram creates an image which has an image duplication effect as well as changes in focus across the field of view. Only the central portion of the image is focused at infinity. On the right panel of Figure 4.3, one can see that by using the corrected insertion hologram the image is free from aberrations across the expanded pupil and over a FOV of 30° x 30°. Two rays were propagated through the waveguide to show the difference between the uncorrected and corrected methods for a +4.5° field
in Figure 4.4. This ray trace shows 2 rays interacting with different portions of the entrance pupil of the waveguide combiner from the same point off-axis. The uncorrected propagation produces image duplication, and the duplicated points are out of focus. The corrected propagation method produces a single point free from aberration across the expanded pupil.

Figure 4.3. Simulated image seen in radiance space through a waveguide at the expanded exit pupil without (left) and with (right) propagation correction [3].
Figure 4.4. Two ray propagation through a curved waveguide without (left) and with (right) propagation correction. Without propagation correction, an off axis point source creates 2 points which are out of focus. With propagation correction, a point source creates a single in focus image point [3].

4.4 Demonstrator

A physical demonstrator of the simulated system was developed using a curved waveguide and HOEs laminated onto the waveguide surface. The waveguide was made from a commercially available 342.9 mm outer diameter acrylic tube. The thickness was 3.175 mm with an inner radius of curvature of 168.275 mm. The HOEs consisted of an insertion and extraction hologram which couples and corrects the TIR propagation within the waveguide and extracts the light toward the viewer.
The insertion hologram was recorded in a transmission hologram geometry with a frequency doubled YAG coherent 532 nm laser. The hologram was recorded on Covestro Bayfol HX200 photopolymer which was laminated to the outer surface of the waveguide. A 25.4 mm right angle prism was index matched to the waveguide using an index matching oil and a plano-concave cylindrical lens. The radius of the cylindrical lens closely resembled the curvature of the waveguide. The object beam had astigmatic power where the focus was designed to be at 0.3 x 171.45 mm. This was accomplished by introducing an \( f = 100 \) mm cylindrical lens 34.3 mm from the right-angle prism hypotenuse face. The reference beam would be a collimated beam onto the curved surface of the waveguide. This required that the power of the reference beam would match the power of the curved waveguide outer surface. An astigmatic telescope was formed using 2 cylindrical lenses with \( f = 100 \) mm to achieve the appropriate power which matched the waveguide surface which was calculated to an effective focal length \( f_w \) of 351 mm. The reference beam was sent through the prism face which allows a total internal reflection to interact with the insertion hologram at 0-degree incidence. This recording geometry allows for the use of the insertion hologram without any extra lenses or coupling optics and can be seen in Figure 4.5.
Figure 4.5. Recording geometry for the insertion HOE showing the virtual focal points for the object and reference beams. The object beam focuses at 0.3R from the waveguide outer surface while the reference beam focuses at the focal length of the waveguides outer surface for a 0 deg incidence angle. Cylindrical lenses are used in the recording to give the necessary power to the HOE [3].

The extraction hologram was recorded in a reflection geometry with the photopolymer laminated to the outer surface of the waveguide. The extraction hologram was recorded using a 532 nm writing laser beam coupled with the insertion hologram as the reference beam. The object beam is a near collimated beam which sets the virtual image distance of the display. Using the insertion hologram simplifies the process because the extraction hologram consists of different segments which receive light at different angles but extract at the same angle according to a global
coordinate frame. The extraction hologram was recorded with a single large, collimated beam. A section of the beam is diffracted by the insertion hologram to be coupled into the waveguide with the appropriate propagation correction and serve as the reference beam for each hologram section. The sections of the beam which are incident on the extraction hologram serve as the object beam.

4.5 Results

The eyebox was expanded by 5 times in the horizontal direction through the curved waveguide. An image of an incident 532 nm laser beam on the insertion hologram is coupled and extracted 5 times by an extraction hologram is shown in Figure 4.6. The efficiency of the extraction hologram was not modulated enough in this demonstrator due to hazing which occurred in the hologram during the pre-exposure process. This can be seen in Figure 4.6. as the brightness of the beam decays across the expanded pupil. The hazing may be a result of poor waveguide surface quality causing diffuse surface scattering to be introduced into the hologram recording.
Figure 4.6. Long exposure image of the curved combiner demonstrator extracting an incident 532 nm laser beam multiple times across the expanded pupil [3].

A 1951 United States Air Force Resolution Target was imaged through the waveguide to determine the quality of image and was illuminated by a polychromatic source. It can be seen in Figure 4.7. that group 3 element 3 of this target can be seen and corresponds to a resolution of the extracted image to be 18 cycles/deg, this can be compared to the waveguide combiner demonstrated in section 2.4 which had an extracted image with a resolution of 29 cycles/deg. When measuring the FOV, it was seen that a polychromatic source expanded the FOV to a maximum of 13° (H) x 16° (V) with 532 nm accounting for the central angle.
Figure 4.7. Airforce resolution target imaged through the curved waveguide showing a resolution of 18 cycles/deg at group 3 element 3 [3].

To test the effects of correction in the combiner a 2nd combiner was created which did not have the correction in the insertion hologram. The insertion hologram was a linear grating which would couple the light to TIR through the waveguide. The extraction hologram was recorded in the same procedure as the corrected version using a single beam and the insertion hologram producing the reference beam for the recording. The difference in extracted images is shown in Figure 4.8. where the main aberration seen is image duplication in the uncorrected combiner.
measured to have a difference of 2.4° between the duplicated images. This image duplication effect was also seen in the computer simulation when comparing the correction of the insertion hologram to the uncorrected. The image was captured by overlaying the virtual information from the combiner with an image of a road which was near collimated by a lens so that they would be on the same image plane (i.e. infinity). This allows for the user to not accommodate between the virtually projected information from the curved combiner and the background. The arrow and text “65MPH” seen in Figure 4.8. were projected by a pico projector which had its pupil relayed to the insertion hologram of the curved combiner and has a polychromatic source.

![Figure 4.8](image)

Figure 4.8. Left image is seen through the corrected waveguide while the right image shows image duplication of 2.4 degrees seen through an uncorrected waveguide [3].
For this demonstrator, degradation in the image as a function of pupil expansion was noticed and determined to come from the surface quality of the waveguide and holograms. The waveguide is a commercially available acrylic tube which has significant deviations in thickness as well as visible surface roughness leading to a highly scattering waveguide. The scattering affects the hologram recording processes which leads to degraded display quality as a function of internal TIR propagation.

4.6 Conclusion and Future Work

With propagation correction via HOEs, a curved waveguide can be used as a combiner. The light undergoes a combination of focusing and expansion through the waveguide which provides a quasi-collimated state within the waveguide to allow for a minimally aberrated curved waveguide propagation.

The difference in power between the front and back surfaces of a waveguide puts a limit on how far light can propagate within a curved waveguide. As propagation distance increases, the negative power of the internal surface dominates the positive power from the outer surface but can be minimized by using thin waveguides.

It is possible to have greater image quality by using a curved waveguide which is manufactured to standard optical tolerances to have better thickness uniformity and surface quality.

Initial ray tracing simulations have shown it is possible to propagate through a 2 dimensionally curved waveguide such as a radially symmetric lens with the front and back surfaces being concentric seen in Figure 4.9. 1-dimension pupil expansion through a 2D curved waveguide needs 2-dimensional correction in both the insertion and extraction holograms. The insertion
hologram needs a correction where the sagittal focus is at 0.3R where R is the radius of curvature and now must include a tangential focus at R distance as described in Figure 4.1. This allows for the light to focus and diverge in this other direction as it propagates by TIR through the waveguide.

Figure 4.9. Non sequential ray trace 3D layout of 1D pupil expansion through a 2D curved waveguide [3].

Similarly, it is possible to extend this method to 2D expansion on 1D curved waveguide in an L-shaped configuration where a redirection hologram is required to redirect the horizontally light
vertically for further pupil expansion. This can ultimately be extended to 2D pupil expansion within a 2D curved waveguide to allow for compact form factor systems which integrate well into HUD and NED systems.

This work has been submitted.
Future work should focus on improving the holographic materials and waveguide quality in the case of a curved combiner, working with different geometries of waveguide combiners and improving augmented reality experience.

The holographic material can be changed to dichromated gelatin for improved efficiency and the curved waveguide can be manufactured to optical quality standards.

One geometry would be achieving aberration free 2D curved waveguide propagation as discussed in section 4.6. This involves designing and optimizing hologram and waveguide parameters and testing the theory by creating a demonstrator.

Another task is toward achieving a true augmented reality experience by satisfying the physiological visual cues. This can be accomplished by displaying images with depth information such as holograms. A hologram generator such as a Texas Instrument Phase Light Modulator (PLM) can coupled into multiple pupil replicating waveguides for a true AR experience by diffracting images toward different insertion holograms to project at different distances.

Additionally, a PLM can be used to supplement a coupling element such as a linear diffraction grating to add wavefront correction for unaberrated curved waveguide propagation.

There are still some challenges to be overcome for this work to lead to a consumer product, but the foundation presented in this thesis will hopefully be a steppingstone.
Bibliography


