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Curved waveguide combiner for HUD/AR

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ABSTRACT

Most of waveguide implementation for HUD or augmented reality combiner are flat pieces of glass because the image propagation does not suffer from any aberration when traveling along their length. However, this type of combiner does integrate seamlessly in front of the viewer eyes and a curved optics would be much more appealing. Using holographic optical elements, we demonstrated that it is possible to correct the aberrations induced by the curved surfaces of the waveguide, and display a aberration-free image to the viewer. This correction applies for different waveguide geometries (1D or 2D curvature) as well as different pupil expansions (1D or 2D expansion). A Zemax model is presented along a curved waveguide demonstrator.

Keywords: Holography, holographic optical element, head-up display, augmented reality, waveguide, combiner.

1. INTRODUCTION

Recently, a number of augmented reality (AR) and head up-display (HUD) systems have been offered to customers using waveguide technology. In these devices, the combiner is a waveguide into which the image is injected by an optical element, such as an hologram or a prism, and the light propagates by total internal reflection. The light is then extracted out of the waveguide by another element that redirects the image toward the viewer.[1,2] The principle of operation of waveguide combiner is presented in figure 1.[3,4]

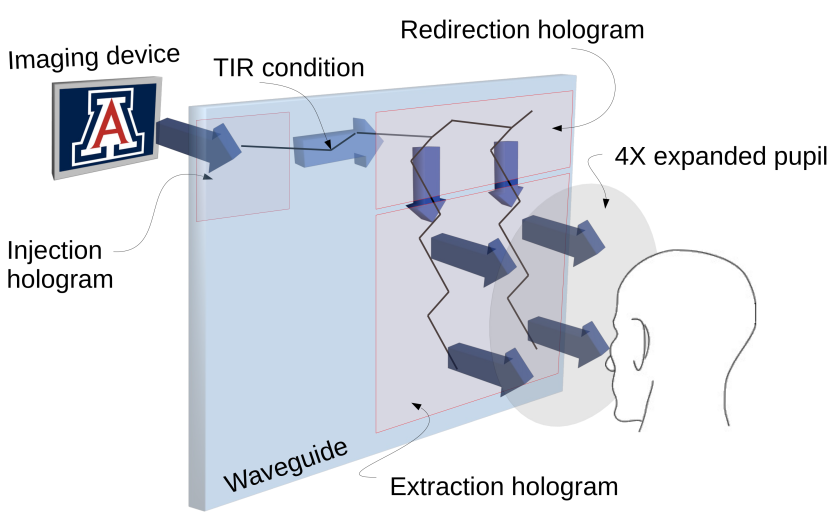

Figure 1. Schematic of a holographic waveguide combiner with 2D 4× pupil expansion.

The appeal of waveguide combiner is that the image can be extracted several times out of the waveguide to increase the pupil of the system (i.e. the eye box), while keeping the field of view (FOV) (i.e. the image size) constant.[5] In other HUD/AR combiner systems, such as reflective surfaces (either semi-mirror or hologram), the pupil and the FOV are related such that when one increases the other is reduced. For example, when the image

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size increases, it can only be viewed in its entirety at one very specific location. Or, to offer a larger eye box, the image size must be reduced. Waveguide combiners are not subject to this limitation, and make them unique and very attractive for HUD and AR applications.

All the waveguide combiner systems that have been introduced recently are using flat waveguides.[6–10] Since the image propagation inside a flat waveguide does not suffer any aberrations. However, flat waveguides are intrusive and, in many cases, it would be advantageous to be able to use curved waveguides. By wrapping around the viewer, curved waveguides would increase the FOV, and would better integrate into the visual environment. A curved waveguide might, for example, be part of a vehicle windshield, a helmet visor, or pair of glasses that better fit the face of the user.

The difficulty of using curved waveguide is that the image propagation inside the waveguide induces some aberrations. In figure 2 (a), an image has been injected into a curved waveguide with a 170 mm radius of curvature, and 3 mm thickness, then extracted by a holographic grating after propagating 25 mm. It can be seen that the image suffer from serious aberrations that need to be corrected if such a waveguide would be used for HUD/AR application.

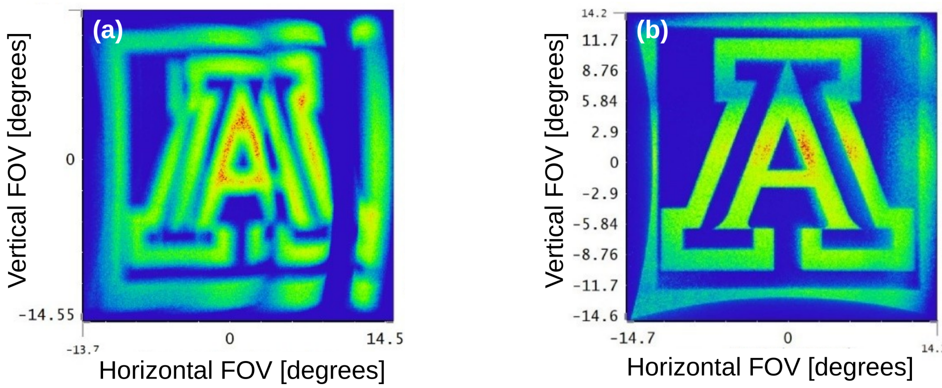

Figure 2. Image extracted from a 1D curved waveguide. (a) Where the injection and extraction holograms are regular diffraction gratings. (b) Where the injection and extraction holograms are holographic optical elements correcting the aberrations from the waveguide propagation.

2. MODEL

In order to demonstrate how to correct the aberration introduced by the propagation of the image into the curved waveguide, we built up a ray tracing Zemax model of a curved waveguide combiner. This system is composed by light engine projecting an image with a $30° \times 30°$ FOV on a injection hologram. The injection hologram is an holographic optical element that redirects the image inside the waveguide at TIR but also provides some level of focusing. An extraction hologram, located 20 mm further than the injection hologram, redirects the light toward the viewer and expands the pupil 3 times. The extraction hologram is an holographic optical element that collimates the light extracted from the combiner so the image is projected at infinity. Finally, a detector the size of the pupil is placed in the path of the extracted image. A 3D view of the system is presented in figure 3.

It was found that to be able to extract an image without aberration, the injection hologram should have a focal distance that is 1/3 of the waveguide curvature instead of being collimated. In our case that is $f = 170\ mm/3 = 56.6\ mm$ in the direction of the waveguide curvature, whereas the image is collimated in the other direction. This way, when the image is reflected by the bottom convex surface of the waveguide, it gets expanded and then refocused by the reflection from top concave surface as presented in figure 4. Each TIR from top and bottom surfaces compensate for each other and the image travels without aberration.

When reaching the extraction hologram, the image is not yet collimated inside the waveguide. To correct for this defocus, the extraction hologram also has some optical power so the extracted image is projected at infinity. It has to be noted that the angle of extraction varies according to the location of the extraction hologram to

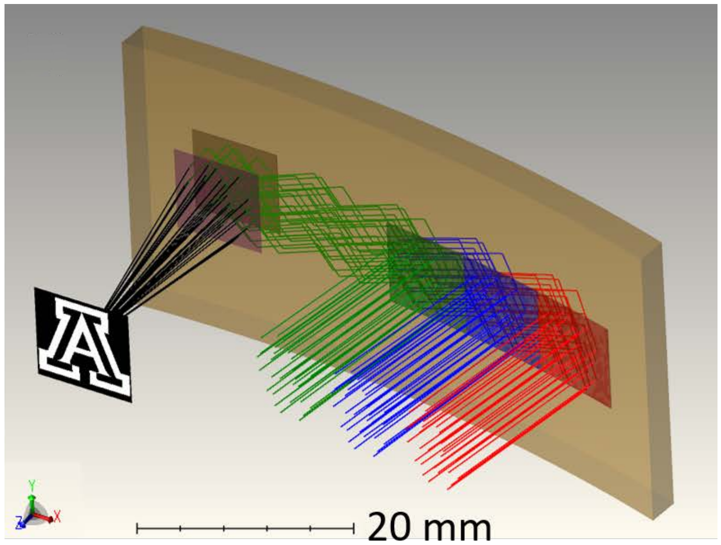

Figure 3. 3D layout of the curved waveguide ray tracing model showing the projection optics, the curved waveguide, and each hologram section. The waveguide is 3 mm thick and has a 170 mm radius of curvature in the horizontal direction.

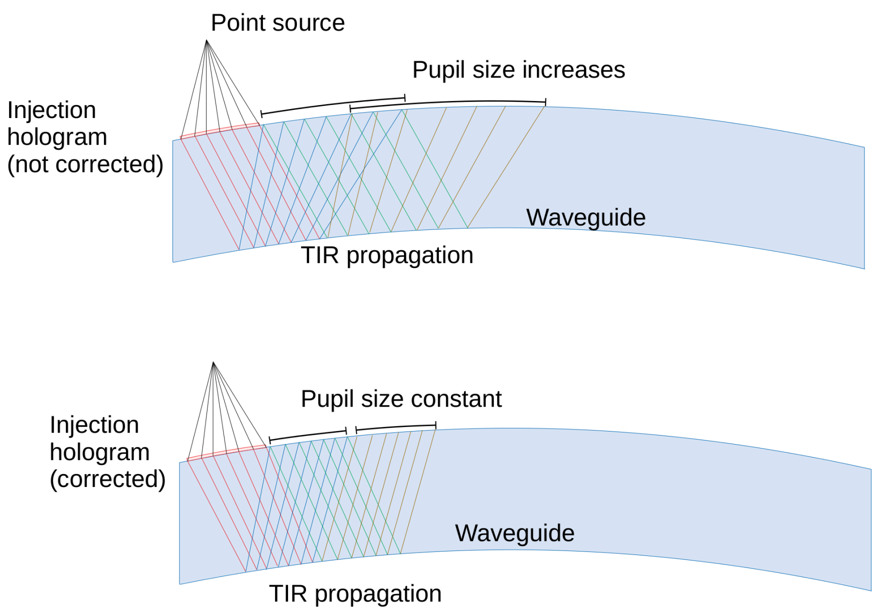

Figure 4. Cross section of the image propagation inside the curved waveguide. Top: without correction from the injection hologram the image expand and its extraction will present aberrations. Bottom: the injection hologram refocus the image so when it gets reflected by the bottom surface, it does not expand and can be extracted without aberrations.

adjust for the curvature of the waveguide. Without this correction, the beams extracted earlier would not be parallel to beams extracted after further propagation in the curved waveguide.

By applying this correction scheme in both the injection and extraction holograms, the image projected to the viewer has no aberration as it is shown in figure 2(b).

3. DEMONSTRATOR

In addition to the ray tracing model, we have built a laboratory demonstrator that showcases the possibility to use a curved combiner for HUD and AR applications. The system parameters are the same as for the ray tracing model, and the waveguide is part of an acrylic tube that has been cut away.

The injection hologram has been recorded using astigmatic beams formed by using cylindrical lenses in order to obtain the different focal distances in the horizontal and vertical directions. The extraction hologram has been recorded by using the propagation beam as a reference beam, and a collimated beam as an object beam. This ensures that the extracted beam is, indeed, collimated.

Both injection and extraction holograms have been recorded in Bayfol photopolymer using a 532 nm doubled YAG laser, and further processed by UV exposure.

A picture of the combiner is presented in figure 5, where the curvature of the waveguide can be appreciated, as well as how the extracted beams are collimated and parallel to one another. The beam intensity is decreasing the further away they are from the injection hologram because the extraction hologram was recorded with constant diffraction efficiency. To equalize the extracted intensity, increased efficiency according to propagation distance is needed as explained in ref 4.

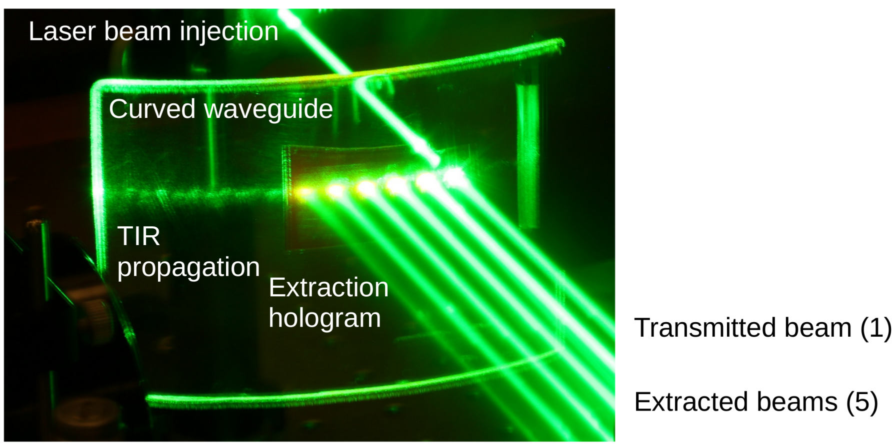

Figure 5. Picture of a curved waveguide combiner demonstrator with single laser beam injection and 5 times extraction. Note how the extracted beams are collimated and parallel with one another, which is the condition to display the image at infinity for the viewer.

We used a picoprojector with diode illumination as the light engine for the system and to provide the image for the combiner. Figure 6 present a picture of an extracted image out of the curved waveguide. It shows that the extracted image does not suffer from any aberration other than scattering. We believe this scattering is induced by the surface quality of the waveguide that presents micro-scratches. This explains why the image scattering increases the further away it is extracted. In our demonstrator, the injection hologram is located on the right of the waveguide.

We measured the vertical and horizontal FOV of our system to be 2 degrees and 7 degrees respectively.

Although the image projected by the light engine is polychromatic (white), the extracted image appears green. The injection and extraction holograms are more efficient in the green portion of the spectrum due to the use of 532 nm as the recording wavelength. Full color image can be achieved by using 3 holograms recorded using red, green, and blue laser sources. These holograms can be multiplexed inside the same material for a thin and compact HUD/AR system.

Figure 6. Picture of an extracted image out of the curved waveguide.

4. CONCLUSION

We have demonstrated the possibility to use a curved waveguide as a combiner to project images without aberration. Both the ray tracing model and a laboratory demonstrator that we built have shown that by using holographic optical elements as the injection and extraction holograms, it is possible to correct the image aberrations induced by the light propagation inside the curved waveguide.

Future works include the use of 2D curved waveguide with different curvatures in horizontal and vertical dimensions, as well as combiner with 2D pupil expansion. We also believe that this technique can be used to correct the image propagating in a waveguide with different top and bottom curvatures, which can be used as prescription glasses for the wearer.

This work can find applications in HUD and AR systems where the waveguide can now be integrated in curved elements such as automotive windshield, helmet visor, or pairs of glasses that better fit the viewer's morphology.

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