

# Shaping the Future with Holographic Transparent Displays

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## Abstract

*Holographic optical elements (HOEs) are used nowadays as an innovative approach to realize different optical functions in transparent media and to make glass smart, which was not possible or limited using conventional optical elements such as lenses or mirrors. As a promising application, transparent displays have been developed already for several years. Due to the technical or cost limitations of other approaches, Zeiss proposed a new technology based on HOEs to realize display functions in transparent freeform shaped media, which are scalable for mass production. This gives enormous potential to apply transparent displays in different use-cases such as incorporation into the windshield and the side door window in a vehicle or in an airplane. It could be also applied to any other glass surfaces and transparent media e.g. in the field of public transportation or smart home technologies. In this paper, we will introduce this innovative technology of transparent holographic displays.*

## Author Keywords

Holographic optical elements; smart glass; transparent display; freeform; glass; windshield; vehicle; airplane; smart home; public transportation.

## 1. Introduction

Display devices have been developed for more than one hundred years. In the past decades, the trend was to make the displays thinner, with higher resolution, higher brightness, better contrast, and better color performance, based on which the technologies are developed such as liquid crystal (LCD) displays, thin-film transistor (TFT) displays, light-emitting diode (LED) displays and organic light-emitting diode (OLED) displays. Those technologies are widely applied in devices such as televisions, smartphones, computers, large advertisement displays, automotive displays, airplane displays etc. The displays used to be non-transparent due to the use-cases and the working principle of those technologies. As more use-cases occurred according to new demands from the market, transparent displays have emerged as a new focus of the development of display technology.

As a very important application in the automotive area, the displays are intended to be off the dashboard and move above to the windshield area, which is defined as “head-up”, because the eyes off from street view and looking at the displays below is a risk for the safety and not ergonomic to drive. Therefore, some technologies have existed in the past several years such as augmented reality head-up displays (AR-HUDs) with the virtual image overlapping with the street view or the panoramic head-up displays (P-HUDs) based on the virtual image of LCD displays. However, in the automotive area the trade-off between features (including field-of-view, brightness, color uniformity, transmittance, privacy function) and the packaging space is always a challenge. [1-5]

AR-HUDs with virtual images have the potential to provide an immersive augmented reality function to illustrate the information overlaid with the real scene with adapted distances. As soon as the features are improved the packaging space gets larger, and the position of the packaging is almost fixed due to the use of the windshield as a reflector similar to a freeform mirror.

The compensation and the adaptation to different geometries of vehicles and windshields are also a challenge for AR-HUDs.

The P-HUD is a very compact application to tackle the problem of packaging space. It only needs a thin volume below the windshield to host the LCD displays. The lower part of the windshield is coated with a highly reflective layer to reflect more light from the LCD displays. The virtual image of the LCD displays is visible for the driver and passengers. This leads to some restrictions depending on the use-case. If the driver or passengers would like to have a privacy function and do not disturb each other with different content in the windshield display, it would be impossible because LCD displays usually have a diffusive layer to scatter the light in all directions above the display surface. This could also lead to another issue that the energy of the display is spread into many directions. Therefore, the device needs more energy as input to reach a high brightness in the desired area. Because the light is reflected, the position of the eyebox is strongly dependent of the curvature of the windshield.

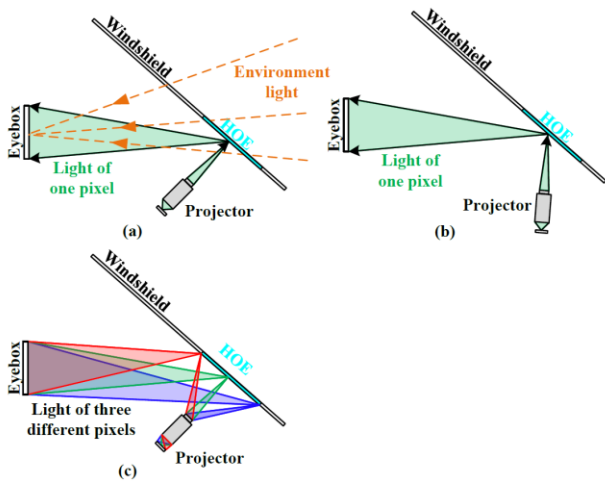
Recent developments in transparent display technology include transparent OLED displays, which offer very good resolution, color performance and brightness. The achievable size is also comparable to regular opaque OLED displays, which is a good solution for both large and small transparent displays. However, the cost is relatively high and the adaptation to curved surfaces might cause further increase in cost. Furthermore, the fill factor and transmittance are interdependent. Therefore, the transmittance stays below 70% so far, if the resolution and brightness must reach a certain comparable level with non-transparent OLED displays.

To overcome the problems of transparency, packaging space, resolution, curvature, and cost issues, Zeiss developed a new transparent display technology based on HOEs. The HOE acts as the display surface, which can be integrated into different shapes of glass and transparent media. The displayed content is generated using an LED- or laser-based projector. The core function of the HOE is to redirect the light from the projector to the eyebox. Due to the properties of diffraction, the directions of incoming and outgoing light can be tailored in a flexible way, allowing for new degrees of freedom for the packaging size and the display position. The redirection of light does not depend on the curvature of the display surface but is based on the diffraction of the HOE. Since the HOE is only responsive for its specified incident light direction and spectrum, transmittance levels of more than 92% can be achieved. Besides, the resolution does not depend on the transparency of HOE but entirely on the projectors imaging capabilities. The working principle of the HOE in the transparent display and the comparison with two other applications as examples will be introduced in this paper. At the end, we will also introduce the reason to choose analog production method for this application. [6, 7, 9, 10]

## 2. Transparent displays based on the diffraction of HOEs

As mentioned above, the display surface is realized using an HOE layer, which is incorporated into a transparent surface like a

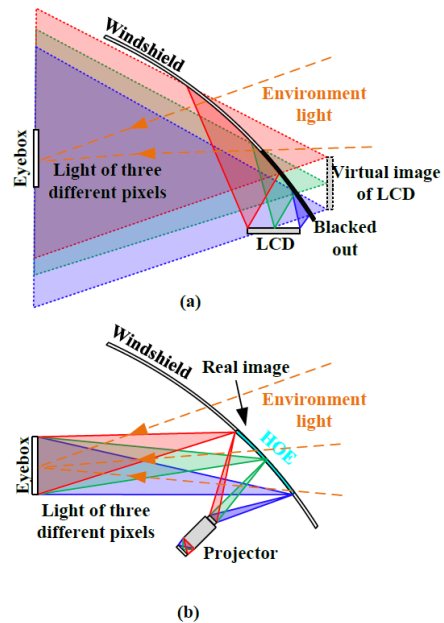
windshield as shown in Figure 1. The light from the projector illuminates the HOE surface. The displayed information, which is shown on the windshield, is created by switching pixels of the projector on and off. If one pixel is on, the light from the pixel is imaged to a point on the HOE surface as shown in Figure 1(a). The light of the pixel comes from a certain numerical aperture (NA) from the projector, which is a fixed light cone. The HOE is manufactured in a way that every point on the HOE redirects the light from a certain light cone to another light cone or even more than one. The size and the direction of the outgoing light cone can be adapted based on the eyebox size and position. In this way, the etendue can be manipulated without changing the size of the projector. This is a main difference to the AR-HUDs. The size of the packaging is decoupled from the increase of the FOV and the eyebox size, which is an advantage of our application. The projector size can be slightly increased as the FOV (size of the display surface) is increased, whereby the current consumer projectors already have very compact and ultra short throw solutions. Therefore, the high transmittance and efficiency of HOEs in redirecting light to the target eyebox is a key point. The diffraction function will only be sensitive for defined incoming light angles and spectrum, which is the light from the projector in the application. For the environmental light, the HOE acts just as a transparent medium as shown in Figure 1(a). Figure 1(b) shows another advantage of the technology that the packaging position is very customizable, because the HOE is adapted to the defined incoming and outgoing light directions. With fixed eyebox position and fixed display position, the projector position can be arbitrary. This is a very important advantage in vehicles due to the installation packaging limitations. In Figure 1(c) it is shown that the light from different pixels on the image plane (HOE) is redirected to the same eyebox area. Therefore, the display is realized with a privacy function that the display is only seen in the eyebox with sharp edges. Once the head of the viewer is moved out of the eyebox, the whole image disappears completely and simultaneously. Since the direction is defined by the HOE, the curvature of the windshield can be arbitrary and can be compensated in the definition of the HOE.



**Figure 1.** (a) The light from one pixel is imaged on the display surface (HOE) and is diffracted from the HOE to the eyebox with sharp edge; (b) The position of the projector can be adjusted without changing the positions of HOE and the eyebox; (c) The light from three pixels on the display surface (the HOE) is diffracted to the same eyebox.

### 3. Holographic transparent display compared to other applications

As previously mentioned, various technologies are available for integrating displays into vehicles. One of the more recent innovations is the P-HUD, which features a large, horizontally extended display that spans the entire width of the windshield. In comparison, the vertical extension of the display is relatively smaller. Typically, multiple LCD displays (usually three) are integrated into the dashboard, positioned close to the windshield. Although these displays are not directly visible, they can be viewed through reflections on the windshield as shown in Figure 2(a). To achieve high contrast, the lower portion of the windshield is often blackened. However, this design introduces certain disadvantages. Since parts of the windshield are rendered opaque, the display can obstruct the driver's view of the road. Additionally, the scattering characteristics of the displays, combined with the curvature of the windshield, influence the propagation of light. This means that light may scatter in directions that are not intended for the driver or passengers, thereby reducing the luminance at the intended viewing positions.



**Figure 2.** (a) Example of P-HUD with LCD-display; (b) Example of holographic transparent P-HUD with LED projector.

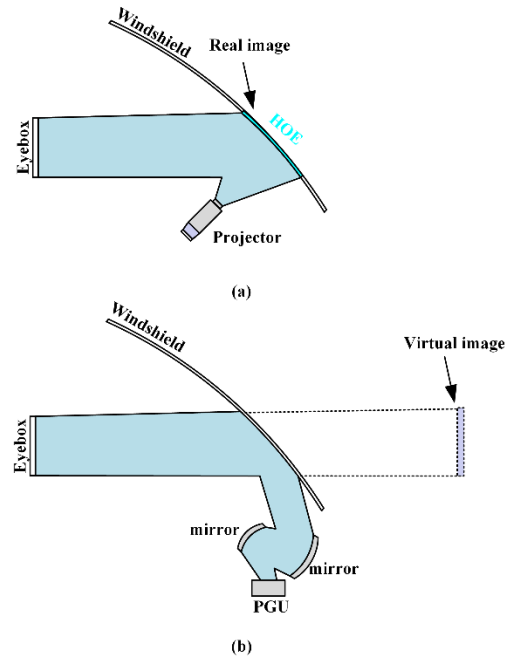
A holographic P-HUD employs diffraction to redirect light from the picture generating unit (PGU) to the driver as in Figure 2(b). Since only a defined light angle and spectrum is diffracted, this technology achieves a very high transparency, with transmittance rates of up to 92% for the ambient light. The diffraction behavior can be customized, allowing the manipulation of light so that it is redirected in specified directions. This enables the creation of various types of eyebox. For instance, certain parts of the display can be made visible exclusively to the driver, while others may be visible for all passengers in the vehicle. By minimizing the leakage of diffracted light, the holographic transparent P-HUD can achieve increased luminance compared to traditional P-HUD systems. Another significant distinction is that the holographic transparent P-HUD utilizes a projector instead of LCD displays. Current LCDs in conventional P-HUD systems consume

approximately 30 watts per display. While traditional P-HUDs can achieve a luminance of around 2500 nits, the holographic system requires only a fraction of the power consumed by an LCD-based system to achieve equivalent luminance, based on luminous flux and power consumption of a standard projector (see Table 1).

**Table 1.** Comparison of power consumption between a classical and a holographic P-HUD.

	Classical P-HUD	Holographic transparent P-HUD	
Eyebox	not defined	900 mm x 80 mm	
Luminance	2500 nits	2500 nits	12500 nits
Power consumption	3 x 30 Watts	3 x 6 Watts	3 x 30 Watts

It is often asked what the differences between the holographic transparent P-HUDs and the AR-HUDs are. They are both head-up displays, which display information in the windshield area to overlay with the street view as shown in Figure 3. One main difference is that the AR-HUD displays the information with a virtual image, which is located some meters away from the windshield as shown in Figure 3(b). The driver could get an augmented reality experience while reading the information on the display such as navigation and speed. The holographic transparent P-HUD displays an image that is directly located on the windshield surface, which is a so called “in-plane” real image as shown in Figure 3(a). Since it can be completely transparent for the street view, it is also an application to improve the safety and experience of the driving. One big challenge of the AR-HUD system is the system size. The current AR-HUD systems are normally based on off-axis freeform mirrors. Therefore, the enlarged etendue due to the large FOV increases the system size. The windshield acts as a freeform mirror in the whole imaging system. Therefore, the packaging position is normally fixed due to the law of reflection. On the other hand, the system performance depends on the degrees of freedom, which could correct the aberrations in the imaging condition, such as positions of the components and the shape of the mirrors. As the system size is limited and the number of optical components is also limited, the correction of aberrations such as dynamic distortion is getting difficult for large FOVs, which means that the two images observed from the left eye and the right eye differ from each other and from different eyebox positions. As mentioned above, the holographic transparent display has a real image. The HOE is not affecting the image quality. Therefore, the two eyes are observing the same object, no matter where the eyes are in the eyebox. There is no issue with the dynamic distortion. Compared to the AR-HUD, the position and the size of the projector of the transparent holographic display are more flexible. Both concepts follow different working principles that aim for slightly different applications. One can decide which one to use depending on the display requirements, the packaging possibility and the expectation of the imaging function. [7, 8]



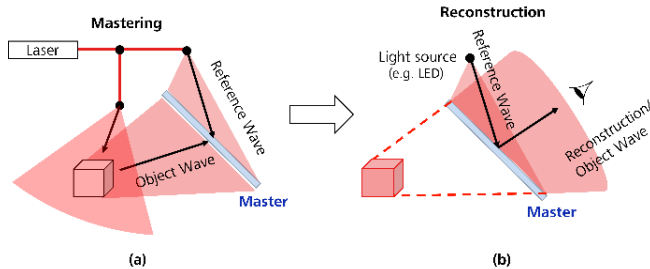
**Figure 3.** (a) Holographic transparent P-HUD with projector; (b) AR-HUD system with freeform mirrors.

#### 4. Advantage of the analog production method of HOEs for transparent displays

The HOE for the transparent display has complex microstructures to realize the optical function due to the freeform geometry of the windshield, the eyebox position, the projector position, the spectrum and the homogeneity. The microstructure on the HOE differs for each point. It is challenging to manufacture those microstructures. Nowadays it is possible to manufacture the HOEs based on digital methods, which segments the HOE into tiny areas. Each small segmented tiny area is a pixel of a HOE, which is also called a hogel, which leads to a grid function overlapping the actual optical diffraction and result in a straylight problem. The manufacturing process gets easier for HOE based on digital methods. On the other hand, the hogels limit the resolution of the HOE. The highest resolution of the display would be the same as the number of hogels. The light will be lost if it hits the gap between two hogels. Therefore Zeiss developed an analog manufacturing method to fully use the HOE as a display without limitations for the resolution. In this case, the whole HOE comprises of continuous, non-pixelated microstructures. The resolution of the transparent display depends only on the resolution of the projector. With the improvement of the projector resolution and brightness, the holographic transparent displays will be also improved correspondingly, and it is not limited by the HOE. Therefore, different projectors can be chosen based on the requirement of the imaging performance and the cost.

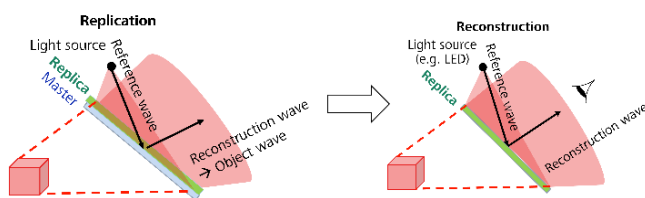
Zeiss is able to manufacture the HOEs for series production based on the replication technology. In this case a first hologram is recorded referred to as the "master" or "original," and the subsequent copies are called "replicas." The recording process starts with creating a master hologram under cleanroom conditions, shown in Figure 4. The laser beam is split into two beams. One of these beams is reflected off an object, which creates the so called object wave. The second one is called the reference beam. Both beams interfere within the photosensitive

material, and information about the wavefront of the light reflected from the object is recorded in the form of an interference pattern - a laterally structured Bragg grating. These gratings appear as changes in the refractive index within the photopolymer. After the hologram is recorded, illuminating from the reference beam direction will cause a virtual reconstruction of the light field reflected from the recorded object. As mentioned in the previous paragraph this recording procedure can also be applied for the case of holographic transparent displays.



**Figure 4.** (a) Hologram master recording; (b) Reconstruction of a recorded hologram.

In contrast, the replication of holograms can be achieved under more common conditions, allowing for production in typical manufacturing environments. During the replication process, previously created holograms are used as masters to reproduce the changes in the refractive index of the photopolymer. To replicate reflection holograms, the non-exposed photosensitive material is placed in contact with the master hologram and then illuminated with a reference light beam. The laser light passing through the non-exposed photosensitive material illuminates the master hologram, which replays the light wavefront information stored during the master recording. This exposure generates an optical copy that mirrors the interference pattern found in the master, resulting in a faithful reproduction of the original holographic image. The reconstruction process works in the same way as with the original master hologram, but now it involves the replicated hologram, as illustrated in Figure 5. [6, 9, 10]



**Figure 5.** Replication process of a hologram.

## 5. Conclusion

The display technology has been highly developed in the past years. To realize transparent display functions with less limitations of the geometry and cost, and to deliver high

performance of brightness, resolution and color, Zeiss has introduced a new technology based on holographic optical elements as an innovative solution. It has shown a large potential in automotive, smart home, and consumer applications. In this paper, we explained the working principle of the holographic transparent display. Two comparisons are shown between the holographic transparent display and already existing head-up display technologies in vehicles. The analog production method is chosen to fully release the potential of the HOE for the display function. With the full manufacturing value chain of Zeiss to realize series production, high quality HOEs could be brought to every car and every home to make the glass smart.

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