Tutorial

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Advances in the design of optical see-through displays

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Abstract: Driven by greatly increased applications, the optical see-through displays have been developing rapidly in recent decades. As a result, some innovative technologies have emerged toward making the display more compact and lighter with better performance. This paper serves as a systematical review on the advances in developing optical see-through displays, including the physical principles, optical configurations, performance parameters and manufacturing processes. The design principles, current challenges, possible solutions and future potential applications are also discussed in the paper.

Keywords: diffractive optics; freeform optics; head-mounted display; see-through display; waveguide.

1 Introduction

Optical see-through displays potentially span various areas such as medical devices, communication, next-generation factory, education and entertainment. The typical applications include head-mounted display (HMD) and augmented reality (AR), with commercially available products from companies like Microsoft HoloLens [1, 2], Lumus [3], WaveOptics [4] and Lingxi AR [5]. Near-eye see-through displays can be categorized into optical see-through systems and video see-through systems. For the optical see-through display shown in Figure 1A, the visual information is projected by a light source and displayed in front of the eye by a transparent optical element without blocking the view to the real world. In the case of the video see-through display, as shown in Figure 1B, it captures the real-world information with video cameras mounted on the head gear, and projects the digital content to observers on an opaque display [6].

The optical element is the most important part in the whole system, which is challenging for the traditional optical design to meet the unique but necessary requirements required by high-end applications. Thus, particular attention should be paid to the performance of optics, as well the optical technologies that are used to achieve the field-relevant functionality. For example, in the field of optical industry, AR superimposes the virtual information on the real world and displays it graphically. It achieves the real-time connection between users and objects with sounds and even haptic feedback. People can see the intuitive colored three-dimensional (3D) images, rather than the traditional documents, with no mistakes and high efficiency, which shortens the time of the operation process and the training cycle of operators [8, 9]. The AR see-through display has great prospects as a productivity tool in contemporary production sites as well as for training people who work in non-conventional working environments. The HMD integrates information on a compact screen, allowing pilots to quickly master the data they need without having to look down the dashboard to remove the gaze from the outside environment [10].

Figure 2 shows the optical functional blocks of an optical see-through display. The display is where images are formed and then image backward to form the pupil (or no pupil) through an optical combiner to the eye pupil. The optical part in the optical see-through display is employed to obtain imaging, exit pupil expansion and combiner functions at the same time, hence making it the most important, complex and costly optical element. It is the connection among humans, the virtual world and the real world. It also defines many parameters including the form factor, the eye box and the wide field of view (FOV). In order to meet specific optical performance, FOV with compact optical elements, large eye relief, along with high

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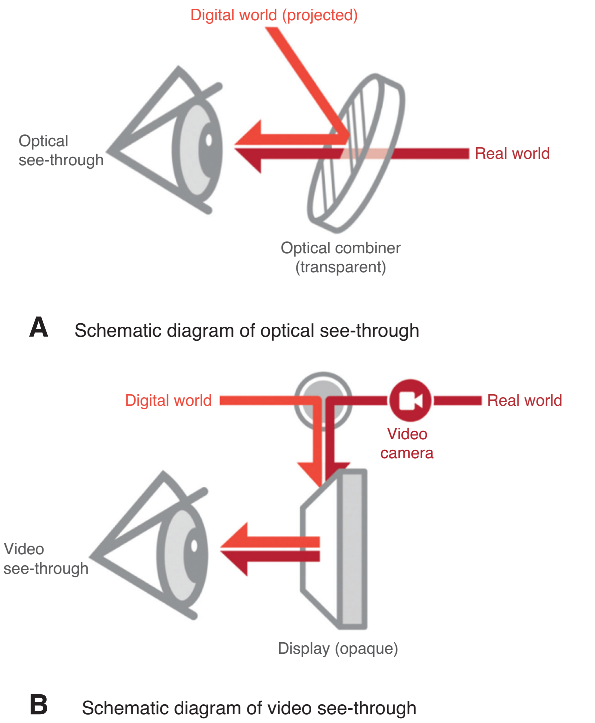

Figure 1: Schematic diagram of the near-eye see-through display [7]. (A) Schematic diagram of the optical see-through display. (B) Schematic diagram of the video see-through display.

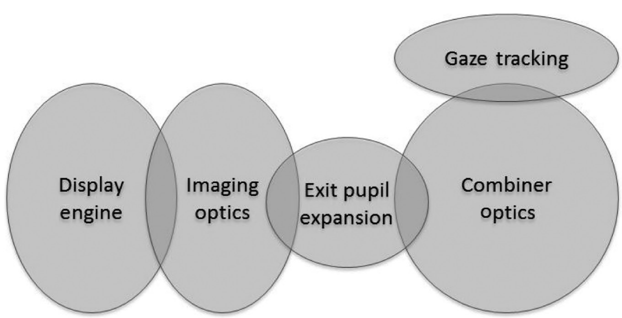

Figure 2: Optical functional blocks of an augmented reality headset system [11].

resolution, small thickness and light weight are becoming the inexorable tendencies [12–17].

Compared with traditional bulkier displays, the optical see-through display is more socially acceptable due to its excellent wearability and portability for mobile applications. It presents more complex demands on optical designs which drives the development of on/off-axis optics, freeform optics, diffractive waveguide and geometrical waveguide. Among these, the waveguide has more advantages and has strong potential to dominate relevant applications. However, some technical difficulties, such as shifting focusing and decreasing chromatic aberration, are still blocking the wide applications.

This paper covers the current mainstream optical designs by describing their principles, developments and applications, especially on the key issues when they are applied in optical see-through display. Besides, the comparison of different optical designs and the challenges in future development are discussed.

2 History

The earliest see-through near-field display emerged during the World War I for a helmet-mounted display around 1915–1917 [18, 19]. However, due to the limitation of technologies, the first AR system was developed in the 1940s, which could only be used as gunsight in military applications, especially in the condition of night and bad visibility. The gunsight was projected in front of the pilots [8]. The first AR system could not be used to support many requirements, owing to the heavy weight and bulkiness limiting eye freedom and causing danger to the pilot's face under a forced landing. In 1961, the world's first see-through head-mounted AR system was invented, which applied the conventional cathode ray tube (CRT) display as shown in Figure 3. The success of this system also inspired years of virtual reality (VR) research and development because it was suspended to the ceiling, which can reduce the weight on people's head [20]. In 1972, the hybrid combination system of lenses and hologram based on diffractive and refractive optics was put forward, which offered a new optical design for the display of optical elements [21, 22]. The main disadvantage of the aforementioned applications is the large keystone distortion.

In 1980, the concept of HMD for pilots' training product in commercial aviation was proposed. In the same year, the EyeTap was invented, including the computer, camera, projector and the micro-display, which allows observers to see the virtual data and the real environment at the same time. In 1984, the first visual coupling system was invented, which connected pilots to aircraft by a half-mirror optical combiner. In 1986, the first modern military HMD, the DASH GEN III, was designed, which provided a collimated image by a spherical visor. The second modern HMD reaching 20° FOV was developed by Elbit system which was limited by the monocular system. The third modern HMD can

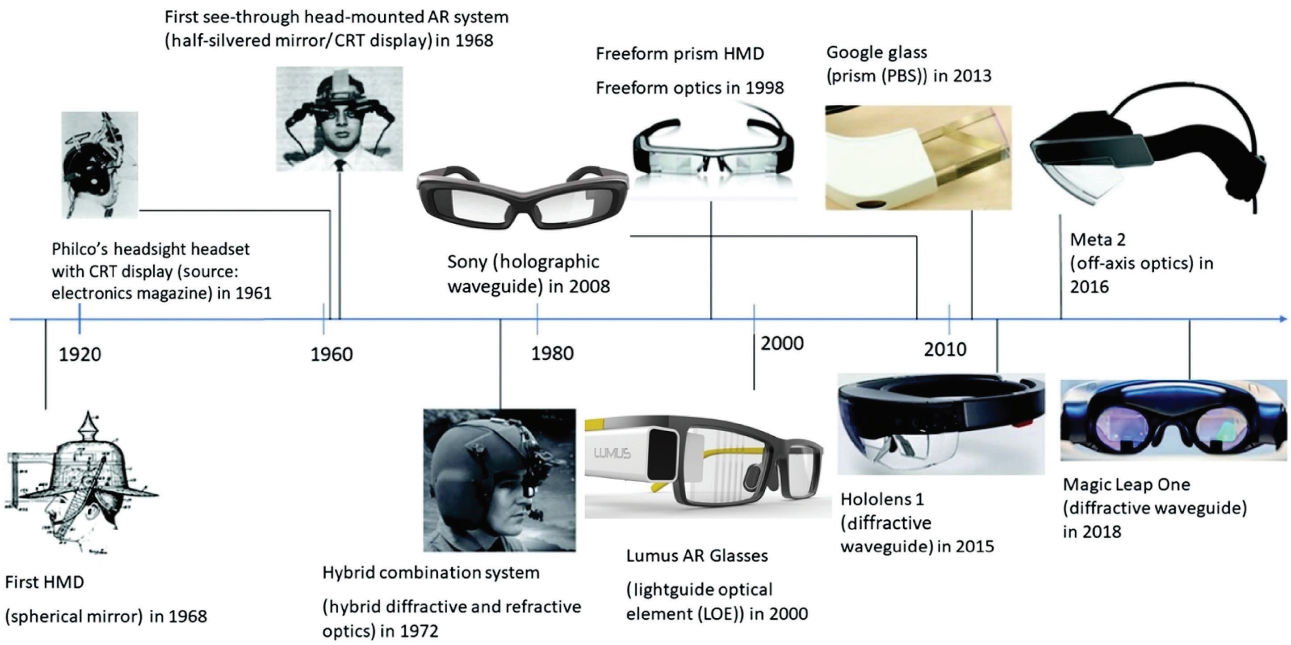

Figure 3: The history of the highlights of the optical technologies [10, 16, 26–30].

reach an FOV of up to 40° [18, 23]. In 1968, a headset with two CRTs from the ceiling was built. In 1997, three characteristics of AR were defined, which are as follows: (1) real and virtual objects in a real (3D) environment, (2) running interactively and in real time and (3) aligning real and virtual objects with each other, which contribute to the future development direction [24]. The freeform prism was first applied to the HMD in 1998 [25]. The ARQuake, which was the first outdoor mobile AR game, was developed in 2000. It means a crucial growth for AR development. In the following years, optical see-through display developed so fast that more and more products were released while some mobile applications were even popularized. In 2013, Google released the wearable optical head-mounted display (OHMD), Google Glass, which is a glass-type of see-through technology, applying the polarization gratings [8]. In 2014, the holographic waveguide structure was released, for which optical transmission visible light can reach 85%. The technology makes the system tighter and smaller. In 2015, the holographic waveguide system HoloLens was released by Microsoft, which achieved the new phase 'mixed reality (MR)'. MR combines the VR and AR and gives us a half-real and half-virtual environment [2]. In 2016, Meta 2 was developed, which applies the off-axis optics. Magic Leap One applying two-layer diffractive waveguides, released in 2018, solves some dizzy problems. Mircosoft HoloLens 2 was released in February 2019, which achieves the FOV at 52°.

3 Key parameters of optical see-through displays

The user experience of observers is related to image quality, the weight and even the wearability of the device. Thus, the optical design and optical elements are crucial to the system performance. There are many requirements needed for different environments and users. It is hard to identify which specific parameter is the most important one; however, in fact, the expected applications of this field are always the driving decisive factor in the optical design. The parameters include [18]:

(1) **FOV.** It is the range of viewing angles available from the system. Humans can see around 120° vertically in binocular vision. A larger FOV within 120° of the AR displays adapts to the human perceptual capabilities. The AR display is also like seeing the world through a window, larger FOV allows us to accept more information. If people are too close to the visual image, the image can only be seen partly. The observer must step back to get the whole image and they can get a great immersive feeling when the FOV achieves 90°.

(2) **Chromatic aberration.** It is caused by dispersion. The refractive index of the optical elements varies with the light wavelength, where the refractive index of most transparent materials decreases with increasing wavelength [31]. All colors cannot be focused to the same point. Thus, there would be color fringes at the boundaries of bright and dark parts of the images, as shown in Figure 4. It may come from propagation dispersion or material dispersion [32].
(3) **Eye box.** It defines the distance of the eye movement of up/down or left/right, in which it does not affect the quality of the image. The optical see-through display always requires a large exit pupil diameter which can not only allow the movements of eyes to observe a larger view, but it can also provide extra tolerance between the display and eye pupil of observers [33]. Larger eye box means greater freedom for users' head movement to observe the whole visual images. Currently, it is usually given as an area within (10–20) × (10–20) mm.
(4) **Eye relief.** It is the distance between the nearest surface of the optical element and human eyes. Larger eye relief allows people to wear their own glasses. And the shorter the eye relief, the lower the FOV. Thus, the preset of the eye relief is crucial to the system. Usually, the eye relief of the spectacle is around 12 mm. The eye relief of the optical see-through display should be larger than that of the spectacle; for example, the eye relief of the product from WaveOptics is 25 mm [34].
(5) **Distortion.** There are two kinds of distortion in the AR display system, one is pincushion distortion, and the other is barrel distortion, as shown in Figure 5. Fortunately, it can be eased by hardware (optical element) and software.
(6) **Form factor.** Compactness, weight and size usually affect the comfort of the wearability. Smarter, lighter AR display is the trend of the system development, which makes work easier. The weight of the system is usually within the range from 50 g to 1000 g.

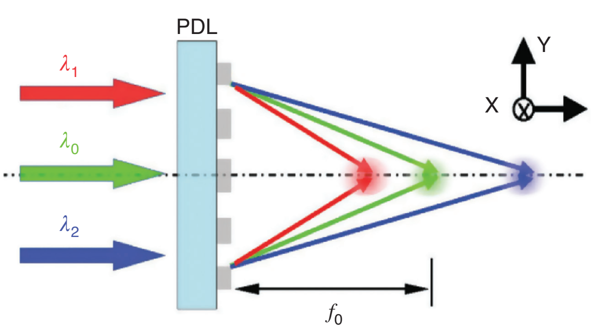

Figure 4: The chromatic aberration refers to the wavelength-dependent focal shift lens [32].

Optical design may not be able to make all the aforementioned parameters optimal at the same time. But optical design is a trade-off process, which needs to be selected according to the requirements of actual use. With the development of optical designs, more and more unique solutions are provided to improve the technology.

4 Optical see-through display design

4.1 On-axis

Birdbath design is a typical on-axis optical system, which combines a spherical mirror and a beam splitter with a simple design and low cost. Most of the AR glasses in the market are used in this way. However, the main disadvantage of the birdbath design is the loss of light. The transmissive light and reflective light passes is Lr × Lt. For example, if the transmissive percentage is 58% and the reflective percentage is 38% (with 4% total loss), the passing light is only around 22% [36]. Google Glass is a

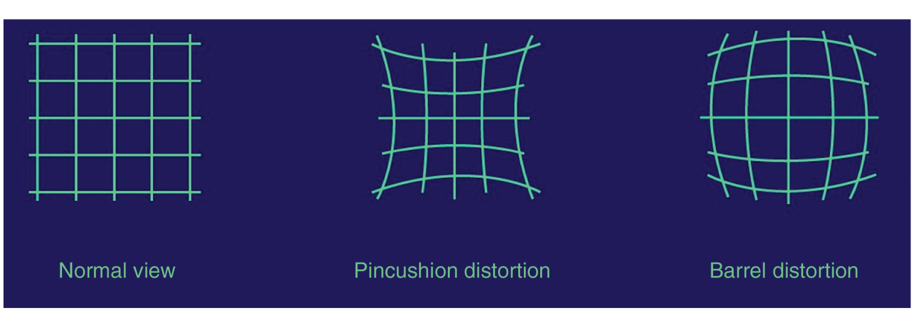

Figure 5: Distortions in the AR system [35].

kind of alternative birdbath using polarized beam splitter (PBS) as shown in Figure 6. PBS is the simplest optical design used to split light beam from the light source, which was always a cube glass. PBS, based on the crystal birefringence of the natural materials or the polarization selectivity of the multiple layers, usually provides high extinction ratio tolerance and a wide angular bandwidth in order to get high-resolution images [28]. When the PBS is applied in the HMD or AR glasses, this would be a cube glass placed in front of the intended sight. PBS is easy to integrate with 0° angle of incidence (AOI) with no beam shift. The optical path of the reflective light is the same as the optical path of the transmitted light. Due to the cube shape, when we need more display field, the thickness of the PBS would be the same as its height and width. For example, if it is needed to have an FOV 3 cm × 3 cm, it is necessary to wear a glass, at least 3 cm thick. Based on the thicker beam splitter, there would be double images or ghost images because of two passes. Due to the polarized system, the maximum light throughout from the real world is more than 45%. It is not only heavy, but it also looks bulky. The shape is not friendly to larger FOV. The solid glass construction also increases the weight of the system. Besides, the polarization beam splitting film has a high requirement on the selected light angle, and the light outside the range does not have a good effect of beam splitting. Hence, the angle of the light in the system should be controlled within the range, and generally the FOV is controlled within the low range of 15°. PBS can hardly get colorful and clear images, with a wide frequency spectrum and a large paraxial range. Besides, the FOV has most restrictive effects on the prism display technology [29].

According to the law of etendue, researchers indicate the relationship between the interpupillary distance (IPD) and the minimum and maximum size of the display and combiner optics as shown in Figure 7.

Considering the manufacturing difficulties and the wearability, the optical design should be in the gray window, as shown in Figure 7. When applying the birdbath architectures, larger IPD always means thicker optical elements. When applying the freeform optics and waveguide, it can be noticed that the thickness of the waveguide is constant but increases the eye box, because the waveguide design folds and restitutes the FOV and losslessly transmits the light with more freedom of optics or total

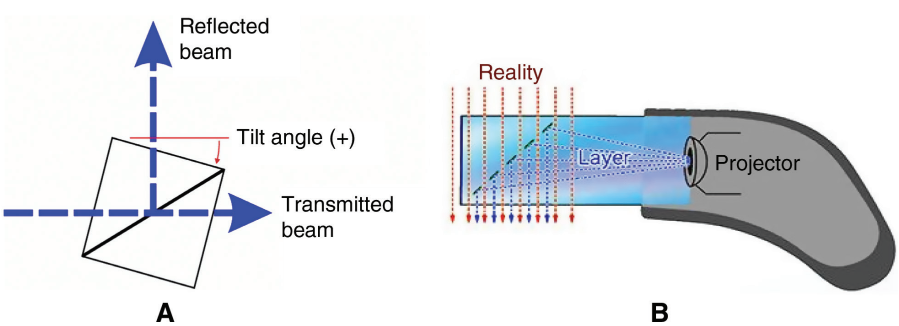

Figure 6: Beam splitter. (A) The principle of PBS; (B) the schematic diagram of Google Glass [37, 38].

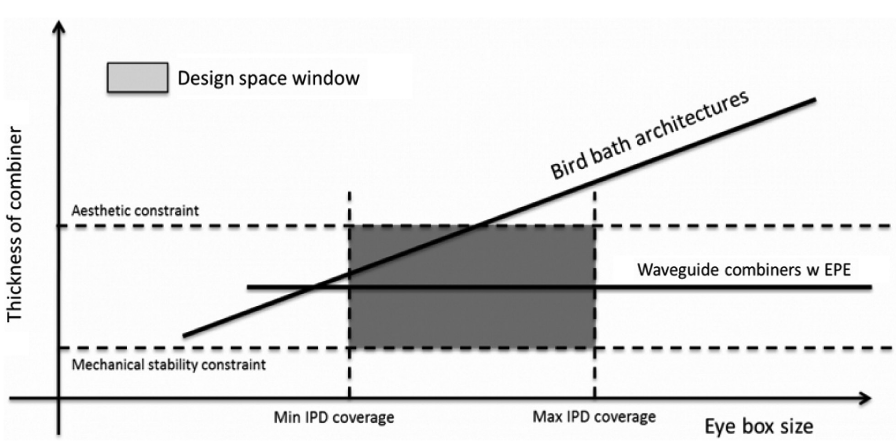

Figure 7: Typical design space for specific interpupillary distance (IPD) coverage and ID requirements [11].

internal reflection (TIR). Thus, on-axis optics has not been able to meet the ideal optical performance.

4.2 Freeform optics

With the development of modern advanced optical design and the improvement of manufacturing precision, freeform optics involves an optical design of at least one freeform surface that has no translational or rotational symmetry on an axis perpendicular to the average plane. Freeform optics has been widely used, which is a trend for smaller and more compact optical systems with an enhanced performance. It is a challenge to integrate the freeform optics and surfaces into imaging, however, which can be overcome by the new degrees of freeform. Additional degrees of freeform reduce the component count and miniaturize the system. Due to the possibility of freeform surface manufacturing, freeform optics is becoming more and more common in optical design, which opens up a new way for modern optical development and research, and even has a profound effect in the optical industry [39–41].

After the method of fabrication and evaluation was explored, Olympus Corporation was the first to apply the freeform prism to the HMD in 1998 [25, 42]. In 2009, a combination of a wedge-shaped freeform prism and a freeform lens was designed, which has a diagonal FOV of 53.5° and an f/# of 1.875, with an 8-mm exit pupil diameter and an 18.25-mm eye relief as shown in Figure 8. In the 2010s, mainstream systems integrated freeform into production, especially in AR HMDs. High precision, state-of-the-art freeform manufacturing is being developed. VR and AR are advancing in research fields, especially the VR and AR HMDs. For HMDs, a compact form with high optical performance, high resolution, large FOV and good image quality is needed. In order to achieve the see-through effect, the free-form surfaces are used with an additional corrector element [43].

Due to the limitation of conventional optics, it was announced that if the traditional surface is made into a curved surface, the splitting effect can be utilized to the most extent. There are some precise calculations in the process of designing the film layer by freeform surface. The range of freeform surface display would also be enlarged, which means the FOV would increase. This technology makes a great progress to increase the FOV, but the thickness is still a problem. In addition, compared with the traditional spherical surfaces, freeform optics has more degrees of freedom and better performance in optical design. The surface of most traditional optics is spherical, which means that the plane is a special case of infinite radius of curvature. The surface of freeform optics has a stronger ability in additionally correcting aberrations as shown in Figure 9 [4, 45]. The shape of conventional mirrors and lens is very simple, which is convex or concave. There are many limitations, such as they do not have certain light-beam paths. Compound compensation can be realized by single freeform optical surface, in the system of which the tolerances can also be redistributed. The optical surface of conventional imaging systems is rotational symmetry, after which the imaging lens should be collinear with the detector and the captured object. As shown in Figure 10, the traditional surfaces are one-dimensional (1D) Q-polynomials, which is an orthonormal basis in slope but the freeform surfaces are orthogonal polynomials [46–50].

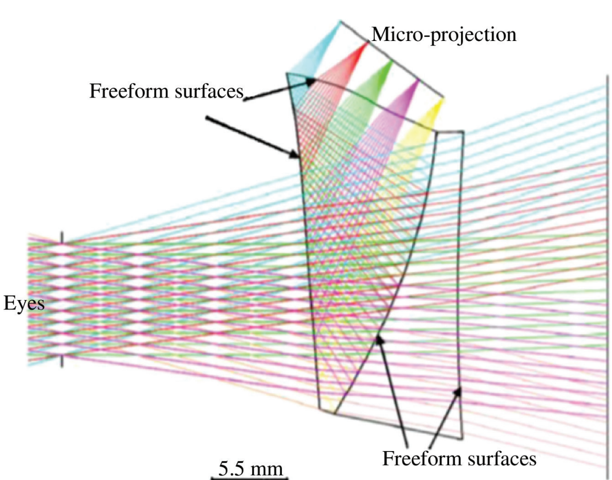

Figure 8: Optical simulation of the freeform surface (FFS) prism [44].

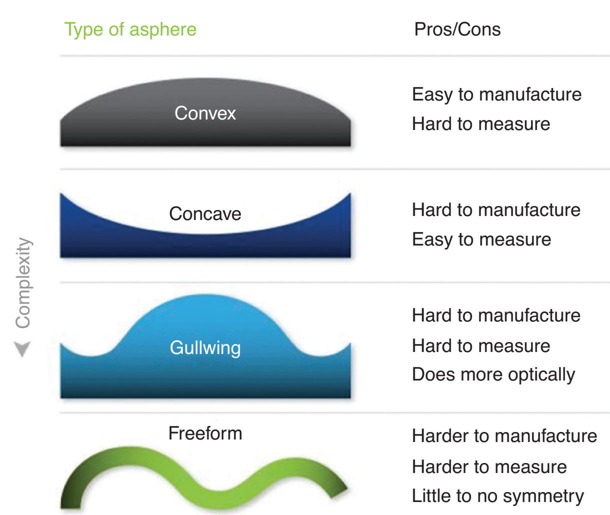

Figure 9: Different types of surface (pros and cons) [45].

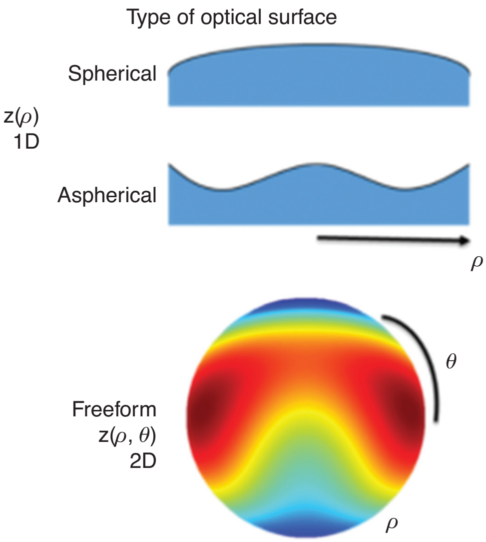

Figure 10: Type of optical surface [55].

Different from the conventional optics, the image detector is just placed at one side of the element because the freeform prism can fold the optical path into one single element [51–54]. Overall, the unique freeform optical design combines the imaging and the HMD eyepiece to achieve the display with no extra devices.

Besides, Meta company combines the freeform with the off-axis system and released the Meta 2. The off-axis optical system is a kind of system in which the optical axis of the aperture does not coincide with the mechanical center of the aperture. Meta 2 is representative of the commercial off-axis optical technology in that the display is not perfectly perpendicular to the combiner, which is a binocular display. The combination of the freeform and off-axis greatly increases the FOV [56].

Manufacturing and metrology are critically important to realize the full potential of freeform optics. For the higher degrees of freedom, diamond turning, milling, grinding and polishing methods are applied to generate the freeform surfaces instead of the traditional two-degree-of-freedom manufacturing processes, such as grinding or polishing. The introduction of new degrees of freedom in freeform optical design is the driving force [40, 44, 57, 58]. However, increasing positioning uncertainly, unique optical form, surface micro-roughness and the mid-spatial frequencies are still a challenge for designers and manufacturers. With the pursuit of extreme optical performance, the imaging quality, thickness and the FOV of the freeform optics are not able to meet some high-end precise applications. Meanwhile, waveguide technology is widely studied and makes it possible to be implemented with these high-end applications due to its better optical performance.

4.3 Optical waveguide

4.3.1 Principle

Waveguide structure has been applied in many fields, such as optical communication and optoelectronics. An optical waveguide is an optical transparent medium device that guides the propagation of light waves or electromagnetic wave in it. Different from the metal-enclosed waveguide, the optical waveguide is TIR on the interface with different refractive index in a limited area. There are two kinds of waveguide, one is an integrated optical waveguide, including a planar dielectric optical waveguide and a strip dielectric waveguide, and the other is a cylindrical optical waveguide, usually called optical fibers. Figure 11 shows the basic structure of the optical waveguide. The refractive index of core (transmitter) is higher than that of cladding (reflector) [59–61]. Any light with an incident angle higher than the critical angle can be totally internal reflected within the waveguide (The critical angle is the AOI where the angle of refraction is 90°. The light must travel from an optically more dense medium to an optically less dense medium.). The lights passing through the optical fiber have no loss in light quantity and can be emitted to the receiver. The materials of the core and cladding influence the refractive index, which determines the critical angle. Thus, the materials and refractive index distribution influence the angle of incident light. The number of the transmitting signals is limited. However, the wavelength has no effect on the transmission.

To meet the 3D and higher see-through optical performance, researchers proposed that waveguide could be applied replacing the half mirror of HMD. Recently, more and more companies applied the optical waveguide in the design of new optical see-through displays, such as Lumus, Lingxi, Mircosoft and WaveOptics. The FOV of previous generations of technology is too small because of the paraxial approximation in optical design. The light near the optical axis has high reductivity and the light far from

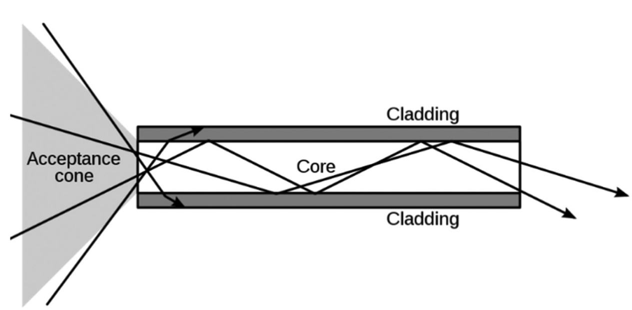

Figure 11: Layout of the fiber/waveguide [59].

the optical axis may have quality differences. Waveguide technology bypasses the paraxial approximation problem in design and calculation. The arrays we see are actually designed to maintain the consistency of the properties of light rays in different directions (large angle light). Optical waveguide structures are thin, which make the optical system small and light weight. The wearable property is critical to the applications. It is an advanced technology to meet the requirements of the optical system including the large eyebox, enough eye relief and large FOV. In modern HMD systems, several waveguide methods are used for AR applications: reflective, polarized, diffractive and holographic waveguides.

4.3.2 Diffractive waveguide

Coupler plays a vital role in imaging. According to the different couple-in/out way, the diffractive waveguide can be divided into diffractive coupler and holographic coupler.

4.3.2.1 Diffractive coupler

Diffractive waveguides are currently widely used in the optical see-through display. The incident light wave is collimated into the waveguide with a certain angle through the first slanted grating (in-coupler). After passing through the waveguide in the coupler, it would finally extract the pupil through the second slanted grating (out-coupler). The diffractive optical element (DOE) is crucial to the system as shown in Figure 12 [8]. The DOE waveguide is thin, light and usually has high light transmission (usually higher than 89%), which enhances wearability. The diffactive waveguide, also called a surface relief waveguide, was patented and first commercialized by Nokia. The transparent AR system Vuzix produced by Nokia and Microsoft Holographic Lens applies the data capture diffractive waveguide, which has low-resolution basic information. The DOE waveguide may be useful, but it would not have as good image quality as objective measurements do. Magic Leap aimed to use a nanometer beam as the light source, the principle of which is the same as the DOE waveguide. The application of nanometer beam source can reduce some defects, but cannot eliminate them, such as flares for the capturing light from the real world. However, they applied the multilayer optical waveguide to solve part of the vergence-accommodation conflicts (VACs).

Diffraction grating observation can blur and distort the image of the real world, and the waveguide softens/blurs the virtual image (the image cannot pass through the waveguide). There are two obvious problems for the DOE waveguide. One is the rainbow effect of the diffraction grating, and the other is the darkening of the real world. The rainbow effect is due to the diffraction effect. The diffractive waveguide has a common problem that the blue and blue-green color shift in the both sides of the image due to the rainbow effect. Meanwhile, the optical efficiency of the waveguide is too low, only a small part of the light can be seen by human eyes. It is estimated that the diffractive waveguide blocks about 85% of the light at the top of the waveguide, especially on the left and right sides of the field of vision, with 86% at the bottom of the waveguide. Different from the prisms, diffractive gratings diffract the light into a series of diffractive orders as shown in Figure 13. Only one of these orders is needed when using the diffractive waveguide, with the rest of the light being not only wasted, but also resulting in reduction of the contrast of the whole system when those orders bounce back in the optical system. If the angle of the incident light is too large to the in-coupler, the light cannot be diffracted/coupled into the waveguide. The function of the grating is influenced by the angle and spacing of the

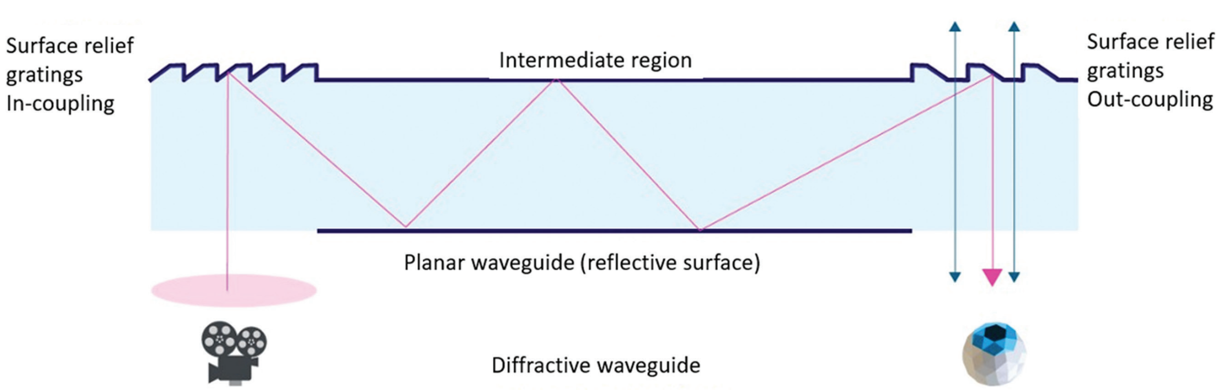

Figure 12: The schematic of the diffractive waveguide [35].

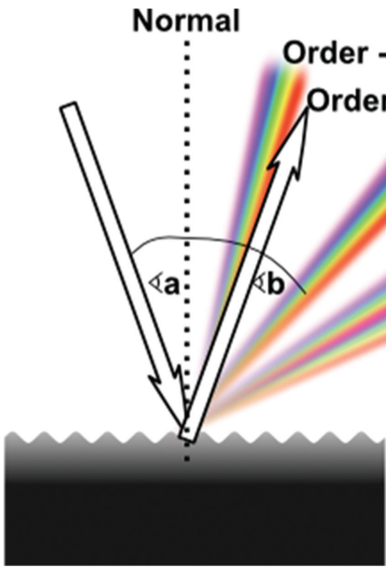

Figure 13: Diffraction grating [65].

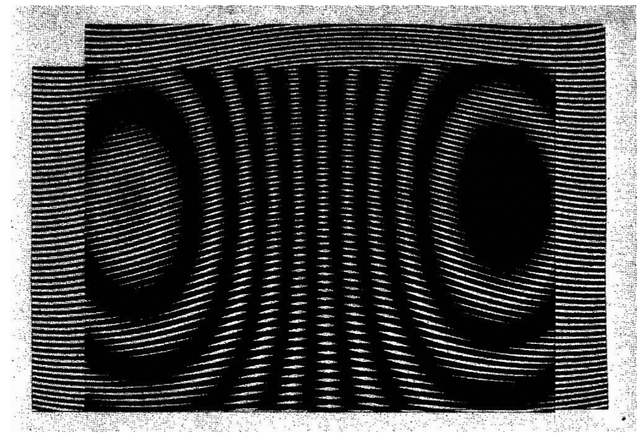

Figure 14: The interference of hologram [75].

orders of the grating, which also affects the visible light from the real world [62–64].

The moulding and ultraviolet (UV) replication processes are applied for the mass production but the high cost is still a obstacle for consumer products [66–69]. Meanwhile, the nano-imprint master manufacturing stage and mass production stage are widely applied because the cost can be controlled and the yield rates are suitable for commercial manufacturing [43, 70].

4.3.2.2 Holographic coupler

The holographic waveguide helmet display technology was developed with the maturity of holographic imaging technology. This technique was developed in the 1990s by Kaiser Optical Systems [71]. The holographic optical element (HOE) includes lens, filter, beam splitter and diffraction grating. The holographic technique is applied to record and reproduce the real 3D image of the object using interference and diffraction principles. A laser which is divided into two beams is used as the illumination source of holographic photography. One beam irradiates the photosensitive film directly, and the other beam is reflected by the object and then irradiates the photosensitive film. Two beams of light superimpose on the photosensitive plate to produce interference as shown in Figure 14. Finally, the hologram reconstructed by the basic principle of digital image is further processed to remove the digital interference and obtain a clear hologram, which includes both amplitude and phase information of the object. When the hologram is irradiated by the coherent laser, the diffracted light waves of a linearly recorded sinusoidal hologram produce two images, namely, the original image (also known as the initial image) and the conjugate image. The reconstructed image has a strong stereoscopic sense and real visual effect. The Maxwellian view is applied in some applications together with the holographic combiner to achieve the retinal projection display [12, 26, 72–74].

The principle of the holographic waveguide is TIR and the diffraction as shown in Figure 15. The system is composed of a mircodisplay, a holographic grating and a slab waveguide. The principle of HOE is similar to that used in the diffractive waveguide. They are all used as the in-couplers and out-couplers. The light wave from the microdisplay goes through the collimating lens, becoming the parallel light beam and then reflected into the in-coupler. The transmission direction of the light in the waveguide will be altered by the diffraction effect of the holographic. When the light beam arrives at the out-coupler, the condition of TIR is destroyed and hence the light is transmitted out of the waveguide to reach human eyes, projecting images on the retina.

For the HOE see-through display, some optical characteristics need to be considered for the manufacturing such as the angular selectivity of the HOE.

There are two kinds of holographic waveguides, one applies the transmission hologram, and another applies the reflection hologram as shown in Figure 16. The spectral bandwidth of the reflection hologram is narrower and the angular selectivity of it is wider than that of the reflection hologram. Wider angular bandwidth allows larger FOV. Narrower spectral bandwidth allows broader spectral source, which can eliminate some color crosstalk problem. Thus, the reflective hologram is more widely used in the holographic waveguide in AR HMDs [43].

The fabrication of holographic grating is critical in achieving the required imaging quality. High diffraction

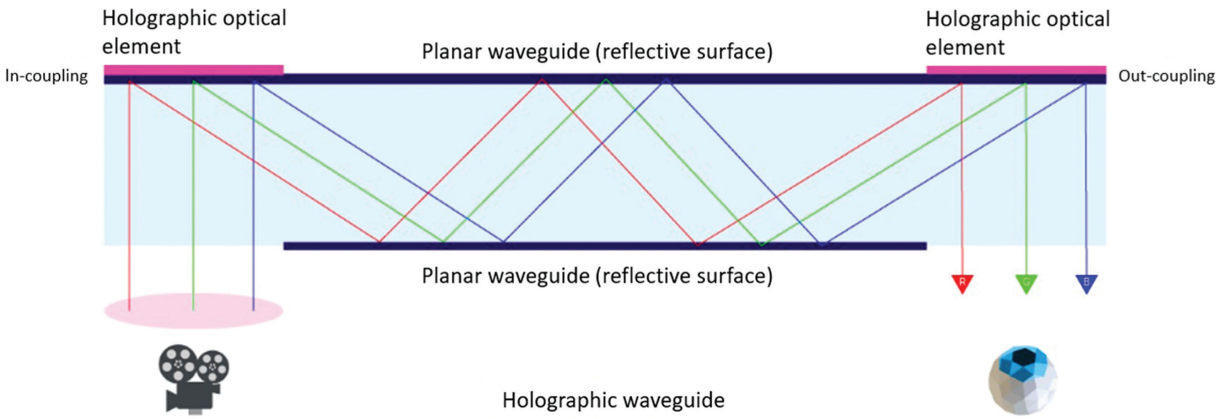

Figure 15: The schematic of the holographic waveguide [35].

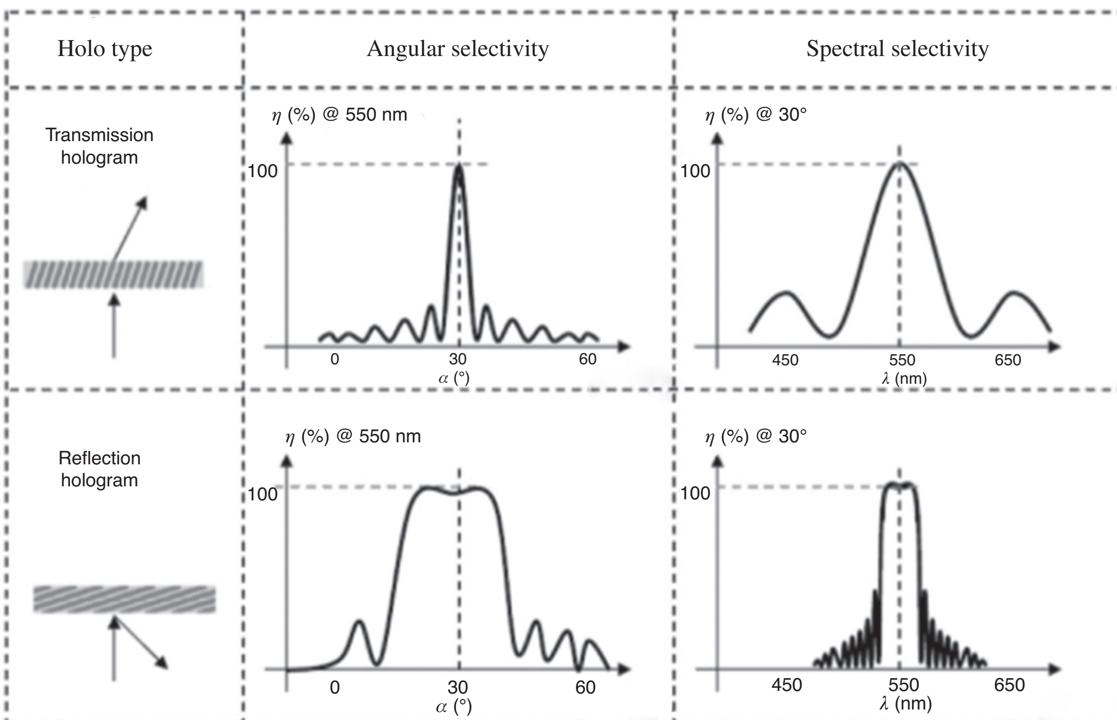

Figure 16: Angular selectivity and spectral selectivity of transmission and reflection holograms [76].

efficiency and image quality can be guaranteed by the high-quality holographic grating. Difficulties in fabricating the holographic gratings appear due to the inhomogeneity during the diffusion process, which leads to optical imperfections inside [77, 78]. New holographic materials are explored to increase the change of the index for a colorful display. The conventional manufacturing method is the roll-to-roll process, which needs high requirements for the flat rates of the plastic substrates [79]. With the development of technologies, DigiLens invented a new method for the volume manufacturing of the waveguide. The diffractive element can be designed by computer, which is a key part for the thickness of the HOE. It is a challenge to the standardization and commercialization of the holographic waveguide [43, 80–82].

4.3.3 Geometrical waveguide

The reflective waveguide is the main geometrical waveguide, which is employed by Epson and Lumus. The images generated from the micro-display are injected to the optical waveguide after collimation. Light travels through the waveguide by TIR. When the light encounters the semi-reflecting surfaces using the traditional coating, the partial light is reflected to the human eyes as shown in Figure 17. Considering Snell's law, the design of the coating must take every particular viewing angle into account, especially the nominal incident direction. There are no exotic components or multilayer coating in the system. It has at least two major surfaces and edges in the light transmissive substrate, made from molded plastic with multiple semi-reflective reflectors placed inside [83]. Therefore, the color non-uniformity would not affect it and the white light would not fade away. The images captured by the eyes come from multiple reflectors, which is a great way to support wide image expansion. There are many kinds of micro-displays (projectors) suitable for the system, including liquid-crystal display (LCD), organic light-emitting diode (OLED) and liquid crystal on silicon (LCOS) [3, 84, 85]. Figure 18 shows the position of the projector and the waveguide, and how the light beam travels in the system. For the projector and the waveguide, they can be manufactured by low-cost standard optical materials. This technology provides high brightness, compact and lightweight optical see-through display.

This technology can be used to achieve wider FOV and larger eye box with more uniform illumination. The display can block 60% lights from the micro-projector. However, the reflectivity of the reflective surface is small, which is less than 1/n (n is the number of the surfaces). For every reflective surface, there are multilayer coatings of 25–30 layers. And they need to be deposited on the substrate (glass or plastic). Then, they are glued together with high presicion and cut at an angle with a high level of parallelism. After being polished, the waveguide is gotten as shown in Figure 19. The uniformity of the coatings, the reflective and polarized efficiency and the cutting precision highly affect the effect of the displayed images.

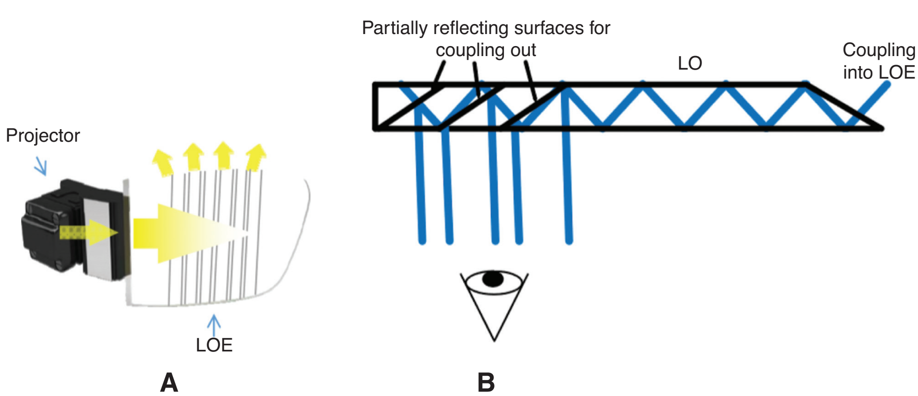

Figure 17: (A) The schematic of Lumus' product; (B) the schematic of the reflective waveguide [3].

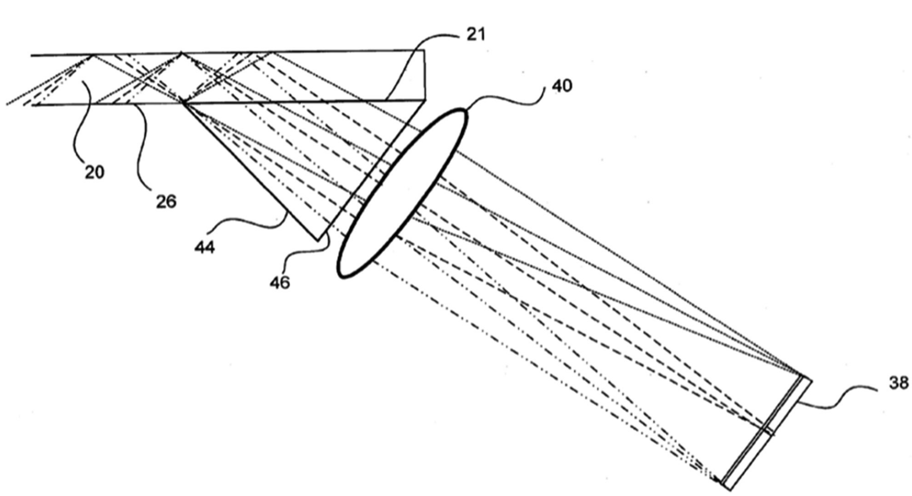

Figure 18: The light beam travels in the system, betweeen the projector and the waveguide [3].

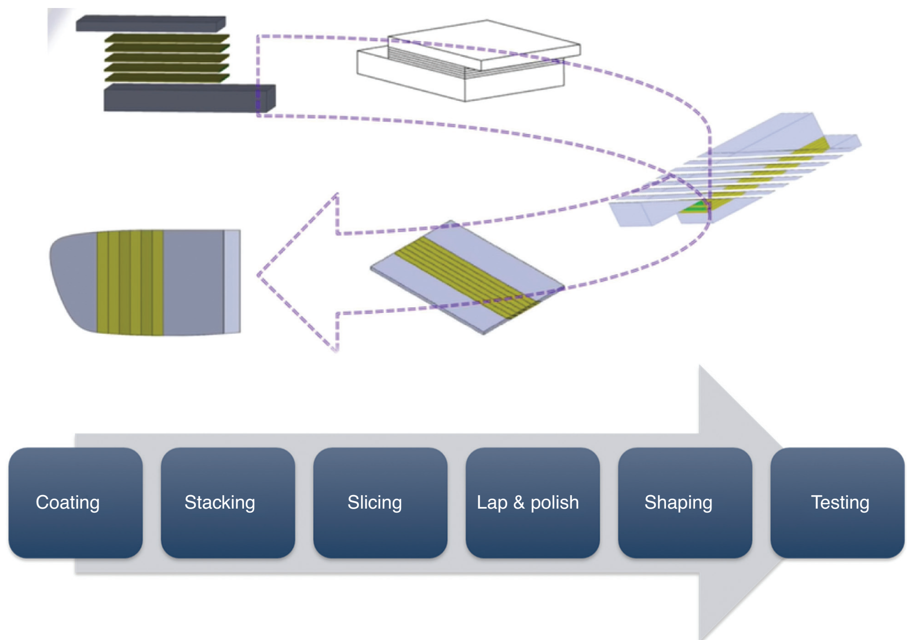

Figure 19: Process of manufacturing polarized waveguide [86].

Compared with the half mirrors, applied by Google, the reflective system has higher optical efficiency and low cost. As there is no loss of light due to the polarization or the grating/holographic effects, the reflective waveguide has higher efficiency in the light power consumption. There are no multi-color issues in the molded plastic substrate. However, due to the extra glass substrate, the thickness is still a problem for this technology. Besides, the FOV of the system is proportional to the size of the reflector.

If a large FOV is needed, the size of the reflector and the thickness of the waveguide would increase, together with the highly distorted images captured by the human eye. In addition, another challenge of this technology is to mould the light guide and the precision of the surface structure to design a system that finds the most compromise for both performance and cost [84]. The reflective waveguide is the most promising waveguide system because of the low cost and no color issue of the substrate.

GodView, a company which focuses on AR/MR core optical modules and smart glasses application demand solutions, released the world's first resin arrayed optical waveguide as shown in Figure 20. Different from the glass material grating waveguide, the GodView resin array optical waveguide technology can produce new nano-resin materials with lower cost and higher plasticity. It reduces the bottlenecks of glass material, such as the difficulty of manufacturing, low portability, weight, fragility and safety. At the same time, it has better performance than glass material with regard to the FOV and the transmittance, which greatly reduces the cost and improves the optical performance and productivity of lens. The thickness of the GodView resin array optical wavaguide is around 1.3–2.0 mm, which is thin and it solves the problem of atomization caused by temperature difference. Resin materials can also provide the property of anti-fall performance and safety. This is also the key reason why the GodView resin array optical waveguide lenses have attracted much attention since they came out [28, 87–89]

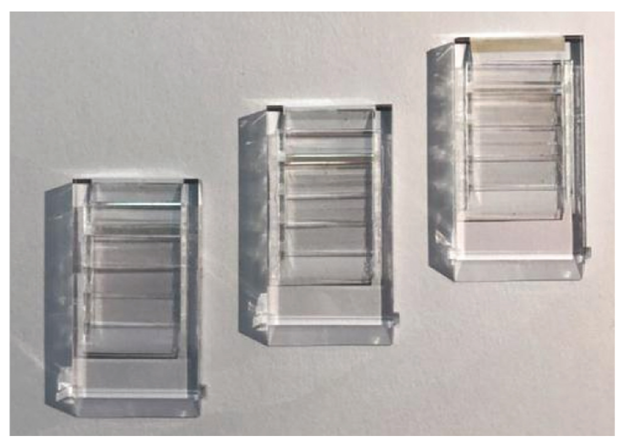

Figure 20: The resin materials applied in the waveguide by GodView [90].

4.3.4 Comparison

As discussed earlier, the optical waveguide is one of the most promising technologies in the optical see-through area.

Table 1 shows the industry players that are applying the waveguide technology and some basic information is listed.

4.3.4.1 Transparency

As shown in Table 1 compared with the diffractive waveguide, the transparency of the geometrical waveguide is much higher. The diffraction gratings soften or blur the virtual images. If more lights from the real world are reflected into the observer's eye, the observer would not see the virtual image clearly as shown in Figure 21. It is defined as waveguide glow when it is out of focus reflections. The contrast and resolution of the images are lower when in a larger bright environment. The image of Magic Leap is even blurrier than that of HoloLens.

4.3.4.2 Color issue

The DOE and HOE are based on the diffractive theory. Diffractive grating has both angular selectivity and

Table 1: Commercially available see-through displays.

Product	Optical element	Transparency	Light energy utilization	Thickness	Color uniformity	Eye box	FOV
Lumus (OE Vision/OE33)	Reflective waveguide	80%	10%	<2 mm	Uniform color	Large	40°
Magic Leap (ML1)	Diffractive waveguide	20%	2%	2 mm	Rainbow effect	Large	45°
Lingxi (AW60/MiniGlass)	Reflective waveguide	90%	15%	1.7 mm	Uniform color	16 mm	36°
Microsoft (HoloLens 2)	Diffractive waveguide	60%	2%	3–4 mm	Rainbow effect	10 mm (H) × 8 mm (V)	52°
Sony (SED-100A)	Holographic waveguide	85%	2%	1 mm	Rainbow effect	9 mm (H) × 6 mm (V)	20°
Waveoptics	Diffractive waveguide	80%	2%	5 mm	Rainbow effect	19 mm (H) × 15 mm (V)	40°

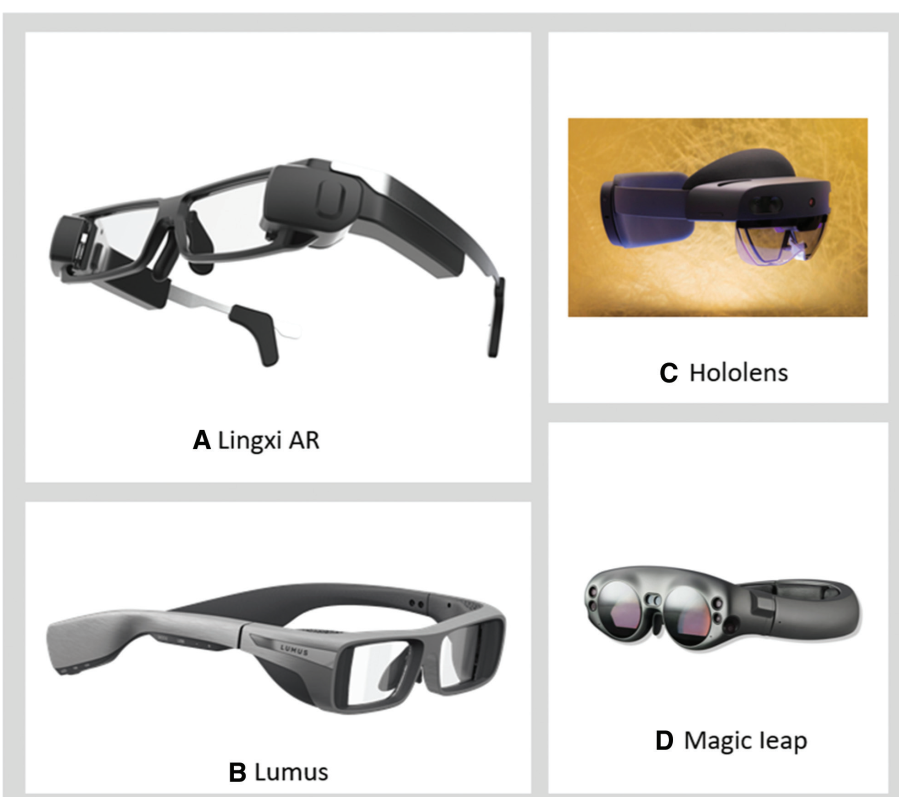

Figure 21: Different kinds of AR products. (A) and (B) LOE is applied; (C) HOE is applied; (D) DOE is applied.

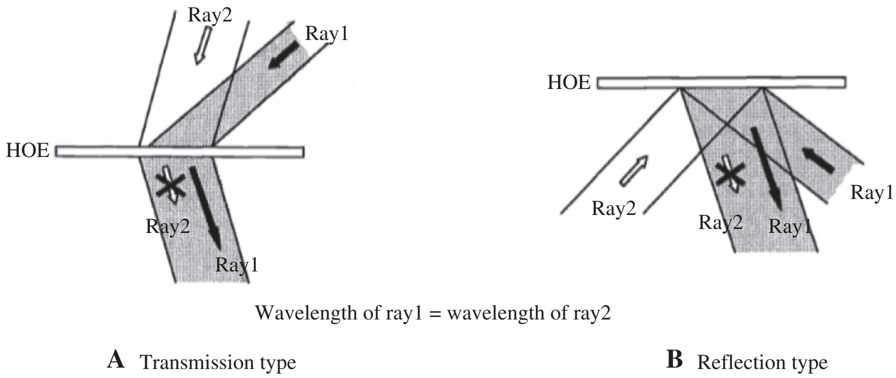

Figure 22: Basic principle of angular selectivity of DOE/HOE [26]. (A) Transmission type; (B) reflection type.

wavelength seletivity. For the angular selectivity, the transmission of the light is determined by the light frequency, and the diffractive intensity is influenced by the incident angle of the light beam, as shown in Figure 22. The diffractive light cannot be seen at a diverged viewpoint, which intrinsically limits the FOV. Another important characteristic is the wavelength selectivity of HOE. It means that when the incident angle of the illumination beam is equal to that of the reference beam for recording, the reconstructive diffraction intensity of DOE/HOE depends on the wavelength of light beam [26, 91].

Another side effect is the rainbow effect, which is due to the fact that the holographic grating can only diffract single wavelength, in which there should be three colors (RGB) sandwiched together, meaning that each of which needed to be exposed by a laser in a special direction, as shown in Figure 23. If single wavelength is slightly diffracted by another color grating, there will be color 'crosstalk', although this can be corrected by software, there are still limitations as the human eye is very sensitive to color [84]. Defects on the surface of the optical element and aperiodic errors in scoring grating grooves also cause scattered lights. Most of the parameters are obtained for the final ideal plan from the optical experiment, such as laser intensity, bandwidth, coherence, center frequency, material formula, exposure time and exposure temperature. However, most of these parameters cannot be obtained by simple optical analysis. The randomness in the process of finding the best parameters through thousands of experiments also increases the difficulty of technology development [5].

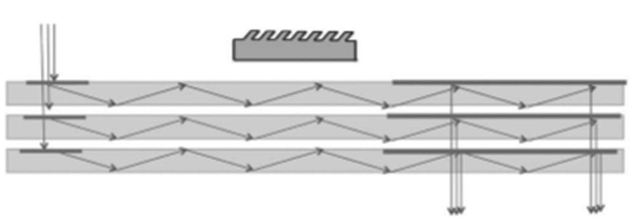

Figure 23: HoloLens RGB waveguides [82].

However, the geometrical waveguide, no matter the reflective waveguide or polarized waveguide, has no grating color issue. They can transmit the lights from the projector to the observer's eyes. The biggest problem of the goemetrical waveguide is the uneven strips because of the folding and unfolding of the images. Precision manufacuring is the key method for the strips problem. Thus, the image quality of the geometrical waveguide is higher than that of the diffractive waveguide.

4.3.4.3 Light energy utilization

As shown in Table 1, the light energy utilization of the geometrical waveguide is much higher than that of the diffractive waveguide. Due to the way of the couple-in, when the light enters the in-/out-coupler, the DOE/HOE influences and blocks some lights reducing the light energy. For practical DOEs, the main factor is that they not only need to change their propagation path when passing through the element, but also they need to have enough light intensity to be applied. The diffraction efficiency refers to the ratio of the light intensity in a certain diffraction direction to the incident light intensity. The diffraction efficiency of the element plays an important role in practice. The eye box and FOV are related to the optical design. The diffractive waveguide and geometrical waveguide both apply the waveguide TIR. Thus, there is no big difference between the two waveguides. Based on the above discussion, it can be seen that the geometrical waveguide is more promising in the future development.

5 Challenges and future development

Although the optical waveguide is recognized as the next-generation key technology for optical see-through display, there is a long way to adapt to better wearability and human perceptual capabilities. Based on the development of waveguide, challenges have emerged and some possible solutions are focused for the future trend.

5.1 Vergence-accommodation conflicts

Considering the stereoscopic imaging mechanism of the human eye, only when the display meets the psychological perception and the physiological perception at the same time, it can be defined as a mature display. The psychological perception can be achieved by affine, occlusion, shadow, texture, a priori knowledge to define it as near or far and the 3D shape of the objects in images. The latency between the real and the virtual image makes the observer feel dizzy, which can be solved by software. The psychological perception can be easily met by these existing designs. However, the physiological perception cannot be easily achieved by current designs.

There are three basic elements in the physiological perception as shown in Figure 24: (1) binocular parallax; (2) motion parallax and (3) accommodation and vergence. The first two can be solved now, but the accommodation and vergence are not solved yet.

VAC helps eyes to shift focus between far and near objects. Focusing on far objects makes the ciliary muscle relaxed while focusing on near objects makes the muscle contracted [93–95]. For example, the observers can lift one finger and make sure there are far trees and near finger in one sight plane. When you focus on the nearby finger, the far trees would be blurred; on the contrary, the nearby finger is blurred. Most optical designs in optical see-through displays have the problem of VAC. In the displayed images, no matter near or far the objects are, they are all displayed in one plane, and the ciliary muscle does not change at all, which obeys the physiological perception. Thus, the observers feel dizzy when they wear the displays for a long time [96, 97].

Only when the light field display presents an infinite number of image planes at different distances, the VAC problem is possibly solved. However, it is hard to achieve that. The Magic Leap One is the first released product which has more than one display plane to solve the VAC. The performance is better than that of HoloLens or any other products. It is known that the light field has seven-dimensional plenoptic function as P (x, y, z, θ, Φ, λ, t). (x, t, z) represents the coordinates in a 3D space. (θ, Φ) indicates the horizontal and vertical angles of the light entering the human eye. (λ) is the wavelength of the light with different colors and different brightness [98]. From above, it can be known that one more display plane means one more dimension. Thus, in order to solve the VAC, the possible method can be increasing the display layers to simulate several different depths to get higher visual quality of the displayed images. Adding any more dimension in the plenoptic function will make great progress in the image display. For the evaluation of this solution, several methods can be applied, such as subjective user studies [93], oculomotor response measurement [99], physiological fatigue indicator measurement [100], brain activity measurements via tools such as electroencephalography

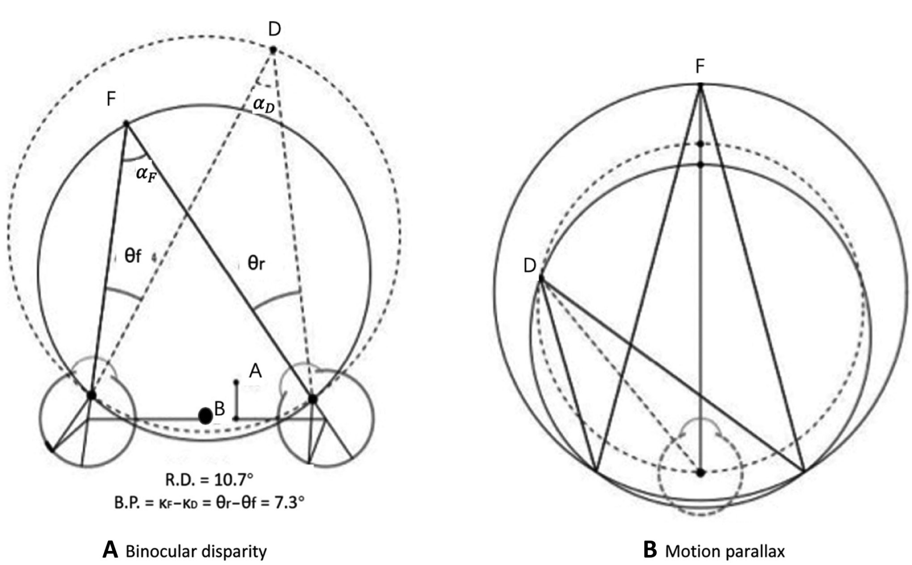

Figure 24: The illumination of the viewing parallax. (A) Binocular disparity; (B) motion parallax [92].

(EEG) or functional magnetic resonance imaging (fMRI) [101, 102].

The sliding optics is the first solution to VAC. A lens was placed between the see-through display and the exit lenses to change the optical depth [103]. Deformable membrane mirrors were proposed, the deformations of which could be controlled by a pneumatic system. Curvature values and maximum displacement of the deformable membrane mirrors are crucial to the eye relief [104].

5.2 Chromatic aberration

From the principle of geometrical waveguide, it expands the pupil by an array of out-coupling surfaces. In the process, the stray light would be generated by some inevitable reflections and as a result some unwanted ghost images are produced by the inconsistency of the angle of the surface arrays. The presence of stray light reduces the contrast and modulation transfer function (MTF) of the image, reduces sharpness and changes the energy distribution of the image plane. In some severe cases, the target signal would be completely annihilated in the background stray light [105]. The stray light would become stronger when the field angle increases in the expansion direction. The ghost image in the edge is more obvious than that in the center. The researchers in BIT University analyzed the causes of stray lights and conclude three types of reasons as shown in Figure 25. A is produced due to the condition that the light rays hit on the entrance mirrors twice.

The blue ray represents the boundary, below which the rays would not hit the entrance mirror twice but would hit above. B and C are the rays that hit on the out-coupling mirror from the left side, and B is incident from below the mirror which reflects the rays while C is from the above [106–108].

From above, it can be concluded that the angle parameter of the waveguide affects the ghost stray light, thus, choosing the suitable angle is necessary, which also limits the FOV. To optimize the parameter, a mathematical model with mass calculation and optimization based on the criterion of stray light and useful light ratio of the waveguide is available to optimize the design with the least amount of stray lights. After designing, the precision of manufacturing is crucial to the mass production [108]. At present, most optical see-through displays are indoor products, the brightness of outside and the light source, such as OLED, LCOS or digital light processing (DLP) will affect the image quality and sharpness. Some applications, such as HoloLens or Magic Leap, apply a hood or darker lens to reduce the brightness from the real world and make the virtual images clear to be observed. The projection can be used with freeform prism with different shapes or something else to correct the aberrations and the brightness.

All optical systems have problems caused by chromatic aberration (dispersion), but the resolution of the human eye is the baseline of the system. No matter the stray lights or the dispersion, the color and the brightness of the light source must be more excellent, which is the first step of the imaging. In the process of designing and simulating the film layer of waveguide for different light,

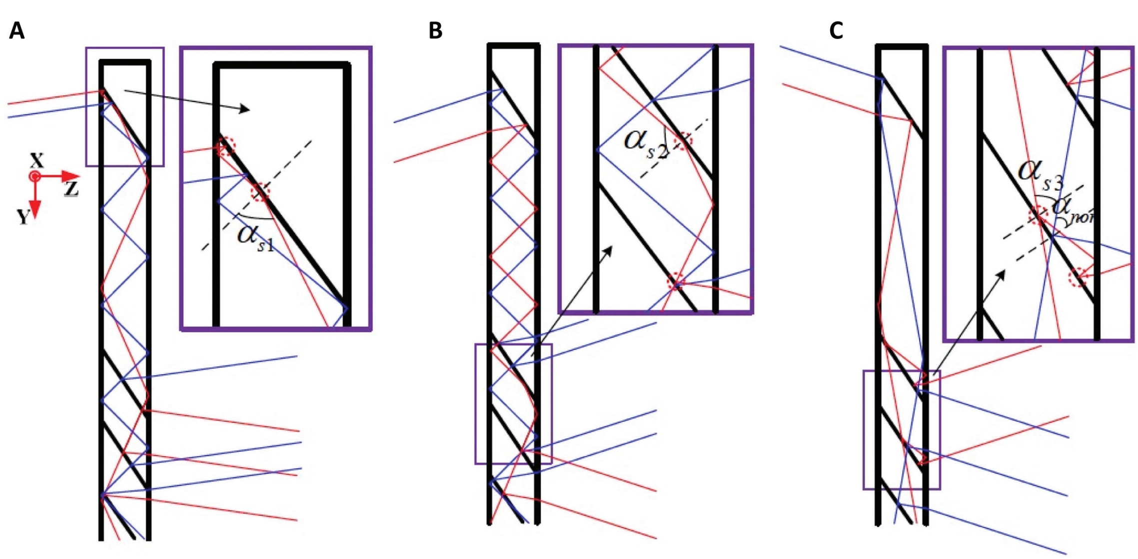

Figure 25: (A–C) Three stray lights in the geometrical waveguide (the blue ray is the normal light and the red ray is the unwanted stray light) [106].

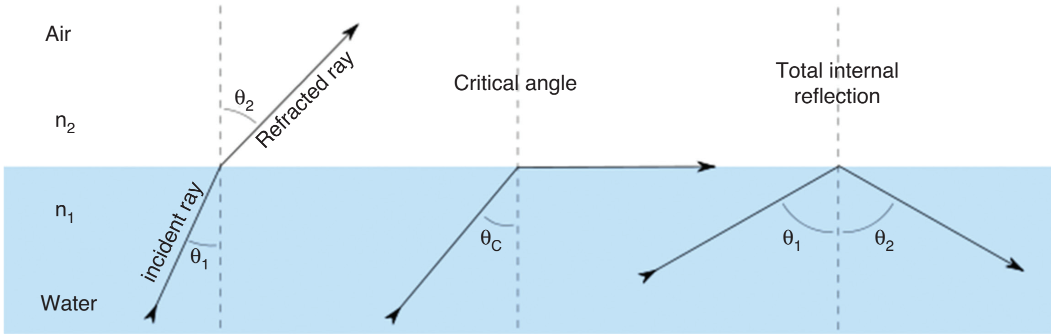

Figure 26: The angles in total internal reflection [112].

researchers should try to minimize the color difference (dispersion) to the human eye.

5.3 FOV

The large FOV is the driving force in optical design. Increasing the FOV is always the goal for all applications. The limitations of the optical design theory and materials have led to a generally small FOV of AR optical systems. The FOV of the waveguide technology is decided and limited by three parameters: (1) the expanded pupil size, (2) the TIR angle of the waveguide material and (3) the distance between each reflection inside the waveguide. Thus, in order to increase the FOV, researchers may solve this problem from these three ways.

For example, the angle of the TIR (critical angle) inside the waveguide is decided by the refractive index as shown in Figure 26, which is the parameters of the inside and outside layers' materials, such as the $LiNbO_3$, SiO_2 and polymer. The refractive index decides the critical angle in the whole system, any angle which is beyond it can be totally internally reflected. The properly combined material layers may not only meet the weight and the transparency requirements, but they would also make the angle of TIR the largest theoretically. Metamaterial is a kind of material which cannot be found in nature. It is made of composite materials such as metal or plastic [109]. Most metamaterials can change the refraction of light which cannot be realized by materials existing in nature. Metamaterials has been applied with holography [110, 111]. It is worth trying it in this area.

Due to the limitation of the waveguide, the images might be divided into two or several parts and after the transmission of the waveguide can be integrated together to the observers to increase the FOV. When the FOV achieves 90°, observers can get a great immersive feeling.

To measure the FOV and the eye box, a new concept, the conjugate focal plane set to the exit pupil of the display, is developed. There would be a two-dimensional (2D) luminance distribution on the plane, which is perpendicular to the optical axis, deriving the FOV or eye box [42].

Besides the above, the lightweight design cannot meet the requirements of the system; the actual production process should also be improved to match the design requirements. To date, the disconnection between theory and technology has always been a problem.

6 Conclusions

In recent decades, the design of optical see-through displays is becoming increasingly important. From the application perspective, there are many critical parameters, such as FOV, compactness, eye relief, eye box, distortion, weight and size and the chromatic aberration. Different kinds of optical functionality of the near-eye see-through displays have been presented in the paper. For the different optical elements, from the on-axis optics, off-axis optics, freeform optics, to optical waveguides, the remarkable progress of above designs in the development is driven by the optical requirements when applied in practical applications.

The geometrical optical waveguides emerged on the market provide higher FOV, lighter weight, larger eye relief and better quality of images for users to achieve immersive feelings and real-virtual connection. However, difficulties of developing the optical waveguide technology have not been overcome, which blocks it to be popularized. This is a challenge for developing waveguides, but it also means a great opportunity in future development. The trend of geometrical waveguide development would be more focused on (1) shifting focusing, i.e. VACs. As the common problem for all see-through displays, it may be improved by multilayer waveguides. From the seven-dimensional plenoptic function, more dimension may increase the human perceptual capabilities; (2) the chromatic aberration. A more precise optical model is essential to reduce the stray lights. The light source affects the image quality, such as the transparency of 3D model and sharpness; (3) increasing the FOV within a proper range. The angle of the TIR, determining the FOV, can be affected by the refractive index of the material. Specific materials may be employed to increase the FOV to get a better immersive feeling. The manufacturing difficulty should also be considered for the volume production. The geometrical optical waveguide in this field is very promising when the cost can be controlled, provided that the manufacturing processes are simple and the above optical difficulties can be solved to adapt to human perceptual capabilities.

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