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Socially Acceptable AR Glasses: Are We There Yet?

Kai-Han Chang, Ali Özgür Yöntem and Kaan Akşit

An Optica incubator meeting explored the role of optical waveguides in developing compact, comfortable and natural eyewear for augmented reality.

As novel optical architectures bring augmented-reality (AR) headsets closer to an all-day wearable, immersive experience, their social acceptability is intensely discussed. Diffractive optical components, meta-optics and creative ways of managing polarization are all making headset form factors more compact. Yet the image artifacts that come with these technologies—forward light leakage (eye glow), ghosting, rainbow artifacts and more—still need to be studied and minimized.

Eventually, technology adoption by the general public depends on social acceptability, which goes beyond hardware architecture. What new value does the headset bring? Does it sacrifice individual privacy? How does it affect social interaction for the user and others? In October 2023, experts in the AR scientific and engineering community came together to discuss these and other questions at an incubator meeting, "Optical Waveguides: A Key to Socially Acceptable AR Glasses?" hosted by Optica's display technology technical group.

Defining social acceptability

An obvious first question is, What is "socially acceptable"? The answer may differ between AR users and bystanders. It will also depend on the value the technology brings to users.

Ideally, AR glasses should have a form factor and optical transmittance comparable to a pair of prescription eyeglasses. Qi Sun (New York University, USA) and Matthew Colburn (Meta, USA) opened the discussion by sharing their research and viewpoints on key challenges to overcome.

Sun described how mixed reality can enhance human performance, bringing "superpower" to human beings, and how the "imperceptibility" of human peripheral vision can be leveraged to reduce headset power consumption, a key issue. His research also covers the task-dependent ergonomics of headset use. Using machine learning to detect the wearer's head movement and to adjust the content accordingly, he pointed out, can influence the head movement and hence increase user comfort.

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Attendees of the incubator meeting, which took place in Tacoma, WA, USA, in October 2023.
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According to Colburn, for an immersive and seamless user experience, a good AR display should have feature characteristics such as a large field of view, high angular resolution, high brightness, accurate color and a large eyebox—all things the community is working on. Meanwhile, for human-to-human interaction, “There is a tremendous value in seeing someone else’s eyes in a conversation,” he said. That adds challenging technical requirements for transmittance.

Colburn strongly emphasized building AR glasses using diffractive components such as binary gratings and blazed gratings—but also mentioned the difficulties in deriving a suitable solution using these classical diffractive components. Liquid-crystal-based volume gratings, he said, might help to tackle the issue. Colburn showed a video of one prototype that displays full-color images through a waveguide that uses such gratings. “We are a long way away from these features,” he said. “But this is why this community is here.”

Are we, as developers, putting too many constraints on ourselves regarding what is socially acceptable? The examples of Bluetooth earbuds and bio-authentication show that users will adapt to a technology that brings sufficient added value and convenience to daily life. Some considerations, however—such as the additional use of biodata stored on headsets to solve specific technical problems—do face substantial real-world constraints. The storage and management of biodata create a potentially significant burden related to data management and privacy regulations, which differ from country to country.

The AR experience varies significantly with individual differences. Thus, while the ideal case would be designing generic hardware that can accommodate most of the population, developing personal AR glasses with a socially acceptable form factor will likely require some customization, including considering the targeted user age group for visual accommodation design. A reasonable virtual image depth and virtual image distance depend on the use cases for which the headset is designed.

In the end, the incubator participants concluded that the answer to “What is social acceptability?” is “It depends.” Among other things, it will depend on the use cases AR glasses are addressing and the value they bring. It will also depend on how well the optical design can be tailored to those factors; a single optical design may not be suitable for all use cases. Moreover, for wide adoption, mass-production capability is critical—and that will be driven by the materials used.

Light-coupling solutions

Özgür Yöntem, University of Cambridge and Jaguar Land Rover, UK, continued with a general introduction to the light-coupling solutions in AR waveguides. As the discussion above suggests, from a human-factors perspective, AR headsets should have the familiar feeling of eyeglasses or sunglasses, with relevant ergonomic features. The headset must be an untethered, stand-alone device allowing prolonged use time (apart from battery time); its weight should be light and evenly distributed. It should not present thermal discomfort or optical aberrations of the world seen through the device, and it should allow eye contact with others—crucial to social communications—as well as the addressing of privacy concerns that partly dictate the sensible placement of cameras and sensors.

One objective of the incubator meeting was to explore optical waveguides as a solution to some of these design challenges. In the AR context, an optical waveguide is nothing but a slab of glass or plastic used as a medium for carrying the light from an image source to the user’s eye, thereby avoiding or reducing the need for free-space optics. Waveguides can be made in almost any size and shape, combined with special optical structures and incorporated into existing prescription lenses.

Early AR headsets have relied on free-space light propagation and “birdbath optics.” The virtual image is created simply by magnifying optics and a display assembly, using a semi-transparent mirror (or a beam splitter) to fold the light path toward the eye—leading to a bulky profile that resembles a birdbath. (Head-up displays in the automotive industry, another emerging application, likewise use such free-space optics.)

The incubator participants concluded that the answer to “What is social acceptability?” is “It depends.” In particular, it depends on the use cases AR glasses address and the value they bring.

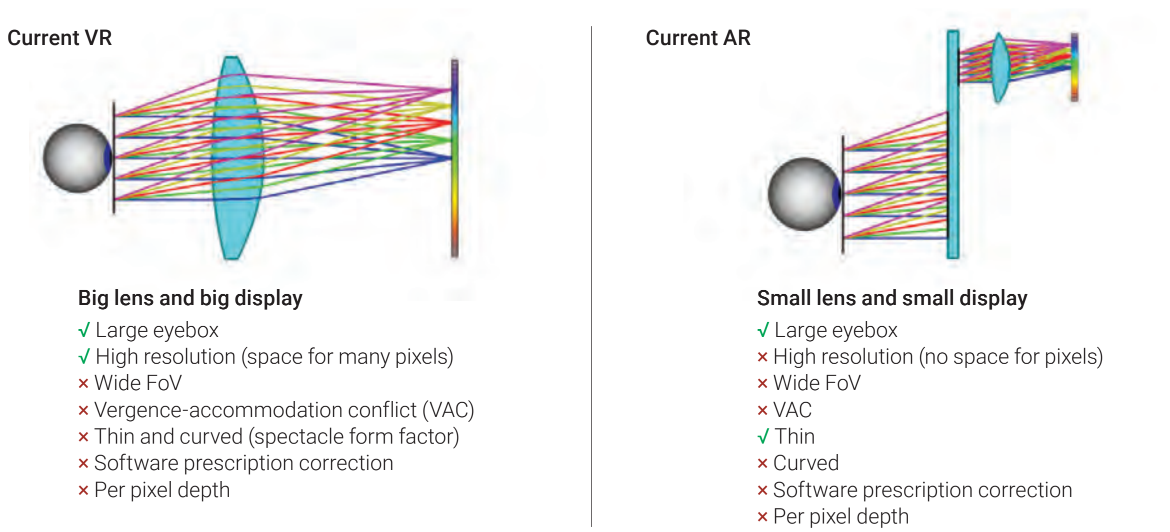
Wearing such devices continuously in daily life to access digital content would have challenges in both comfort and social acceptance. The flatter, thinner optics of conventional eyeglasses, in contrast, are widely accepted as a mainstream accessory in daily life, so similar, flatter optics would be preferable for AR headsets. Waveguides offer one immediate solution for this problem.

Whether plastic or glass, waveguides work on the principle of total internal reflection (TIR). The challenge is to couple the image information into the waveguide, propagate the light with high efficiency and couple it out where the eyes are located. The majority of solutions to the problem of coupling in particular can be grouped into a few categories: surface-relief gratings (SRGs), which constitute the majority of the designs; holographic optical element gratings (HOEs); and pin mirrors. By carefully designing the diffraction angles of SRGs or HOEs, light can be easily coupled into or out of the waveguide. The designs have a small input grating to couple the small image source, and a large output grating to replicate this small image over a larger area, thereby accommodating differences in individual pupil locations and eye rotations.

The nature of diffractive components, however, gives rise to design challenges: multiple diffraction orders, light leakage to the outside world and light efficiency. For SRG-based designs, light leakage is more significant, as the light reaches all parts of the output gratings and couples out of the waveguide in either direction. This elevates privacy concerns, as the outside world can also see what the wearer sees. Moreover, the wearer's eyes are blocked by this light leakage and will not be seen. Instead, they will look similar to a cat's eyes glowing in the dark—not something that is likely to encourage people during their day-to-day social interactions.

Slanted and blazed gratings can increase diffraction efficiency and reduce the light leakage, as can HOEs, the diffraction efficiency of which is significantly higher than for binary diffractive optics. The downside is that HOE production remains a big challenge, as HOEs still need robust recording setups. The holographic material properties, shrinkage and uniformity are also important factors to consider when producing HOEs.

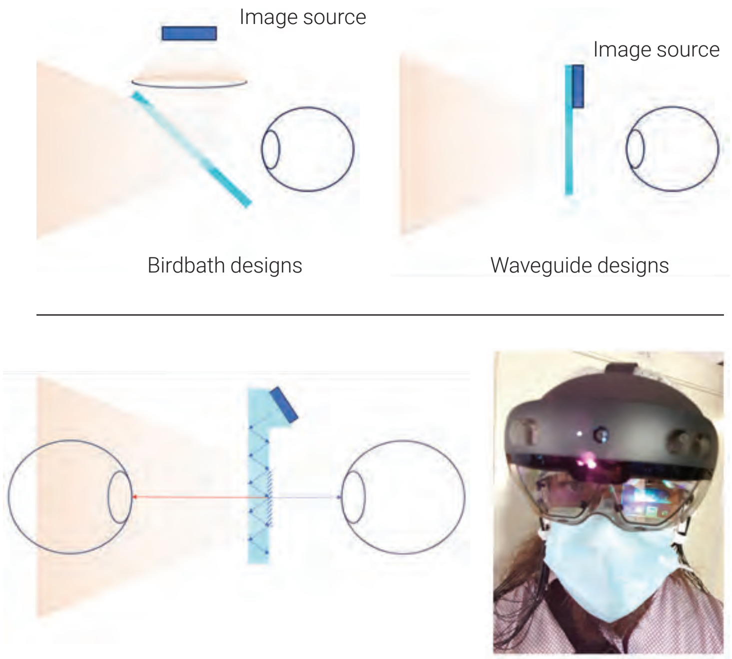
Another concern is the use of the suitable light and image sources for the waveguide and the coupling technology; not all combinations work well together. There are many studies on viable permutations. Currently,



Andreas Georgiou of Reality Optics summarized the current state of VR and AR displays. The incubator meeting suggested that improvements in field of view, resolution, brightness and other parameters—all of which the community is working on—are required for a good user experience.

A. Georgiou

Beyond technical and design considerations, mass-producibility is obviously a key component in success for any product.



Waveguide designs enable flatter, thinner optics than traditional "birdbath" optics (top), but certain waveguide designs can allow light leakage that can raise privacy concerns (bottom).
A.Ö. Yöntem

the most notable technology is microLED-based displays, which could provide brightness levels reaching a million nits (a nit is equivalent to a candela per square meter)—one of the motivations for the current "gold rush" in microLED research.

Design tools and metrology

The incubator meeting also included a dedicated panel discussion on design tools and metrology. The session covered four broad areas.

Emerging computational approaches. Kaan Akşit, University College London, UK, introduced Odak, an open-source toolkit for perception, wave and ray optics, and computer graphics. This tool allows the fusion of deep-learning methods with design and simulation by providing fully differentiable methods based on modern machine-learning libraries. Such differentiability is crucial for optimizing AI applications, Akşit emphasized, citing holographic displays as an important example. The panelists also discussed differentiable ray-tracing applications in computational imaging and camera design.

Improving simulation accuracy. Qi Sun of NYU suggested that hardware-in-the-loop approaches for simulating optical hardware could further enhance the simulation toolkits. Murat Deveci (OptoFidelity, USA) highlighted the importance of metrology tools in ensuring complete traceability when testing products from the component level to the final product. OptoFidelity, he said, is leading standardization efforts like those of the International Electrotechnical Commission (IEC) for waveguide and light engine measurements based on human visual system perception. Most in the audience agreed that accurate measurement data could help enhance simulation accuracy and design processes.

Incorporating human visual perception. The panelists discussed how perceptual approaches like foveated rendering and perceptually accurate colors could decrease bandwidth and computational demands while saving power in future AR glasses. Human visual perception, they concluded, is a key component for crafting next-generation AR displays and visual-experience design, focusing on the temporal aspect of peripheral vision and its implications for display design.

Novel AR designs. As an example of computational design approaches, Akşit highlighted a novel design for AR glasses that involves removing active parts of a wearable display from the AR glasses, providing users with a passive, lightweight optical component that magnifies projections from a static projector in the surrounding environment. The discussion sparked conversations about mobility and the optical-design requirements in such emerging alternative AR systems.

The panelists also discussed other important variables in the design-tools space, including the relative merits of Python's Julia and C++ for optical design and computer graphics; metamerism versus peripheral vision; and the statistical distribution of pixels in image design, emphasizing the importance of considering cone density and resolution when creating displays that replicate reality.

The path to product

Beyond technical and design considerations, mass-producibility is obviously a key component in success for any product. SRG is the main solution currently adopted for mass production of AR-targeted waveguide light-coupling solutions. But could there be others?

Serpil Gonen Williams of Pixelligent, USA, a nanomaterials manufacturing company, described the company's processes and materials, which she said allow high-refractive-index and high-transparency formulations—both essential for AR waveguide applications. Pixelligent's titania- and zirconia-based materials can be deposited in thicknesses ranging from 100 nm to 10s of microns and refractive indices of 1.7 to 2.0 with residual-layer thicknesses of less than 30 nm when nanoimprint lithography is used. They also offer formulations for inkjet-printing processes and can be used in metalens production.

Another materials company, Phosio (USA), is exploring the deposition of high-performance inorganic coatings at low temperatures via common solution-based methods. According to its CEO, Omid Sadeghi, Phosio's vision is to offer the optical industry lower-cost inorganic coatings for both high- and low-refractive-index materials used in optoelectronics. Its nanoparticle-free UV-patternable material is capable of covering a refractive index range of 1.35 to 2.35 with high transparency and low haze.

It is encouraging that companies can already develop, produce and supply the materials required for optical devices in the AR supply chain. Gonen Williams and Deveci pointed out that there is ongoing collaboration within the optical waveguide supply chain covering the entire range of design, production and metrology.

Hiroki Kikuchi (Sony, Japan) emphasized that his company has already demonstrated many products for AR/VR. It produces microdisplays such as LCoS as well, and it demonstrated a full-color AR glasses prototype with HOEs in 2008. Sony has also demonstrated a plastic AR waveguide with HOE concept, although production costs and challenges of recording HOEs on a plastic substrate have prevented these going to consumer products. Moving forward, injection-molded SRG waveguides enable low-cost production and could also prove a good alternative for metasurface optics production.

Joel Kollin (Holonix LLC, USA) highlighted the potential for curved waveguides using wavefront modulation and time-multiplexed outcoupling using switchable gratings, which could help to achieve the desired larger

Tyler Gibson of Magic Leap showcases the company's Magic Leap2 headset.

Content and use cases

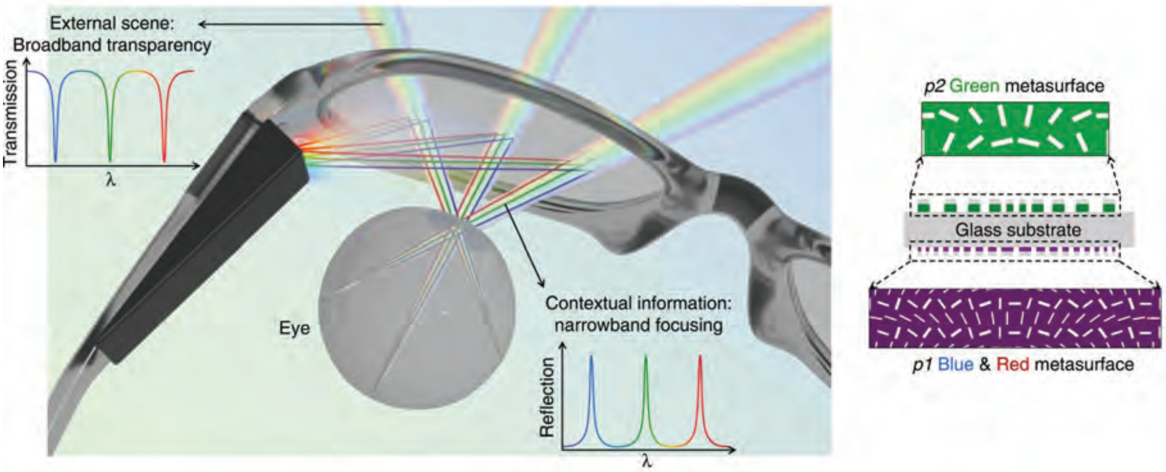
While waveguides, HOEs and diffractive optics preoccupy hardware developers, it is AR use cases and content that draw public attention. In a session discussing these, Tyler Gibson of Magic Leap, USA, suggested that "social" and "acceptance" are two different aspects—buyers can be motivated by the (social) fear of missing out, which can increase the acceptance of the technology.

Purchasing motivations fall into two categories: pleasure (more of a luxury) and utility, such as enabling shopping, enhanced convenience or other specialty functions. Safety considerations may also drive a preference for the headset to be untethered. What sort of convenience can AR glasses bring? Haoshuo Chen (Nokia, USA) shared a few examples in the company's recent research on using AR for enhanced network digital twins, digital maps, indoor guidance, network card identification, interactive remote collaboration and maintenance support.

One comment—"The competitor is not another headset, but the smartphones"—spurred enthusiastic discussion. While smartphones have demonstrated AR applications for gaming, navigation and video chats, those applications require that the user hold the phone by hand, a challenge for many two-handed tasks AR could facilitate. AR glasses, by contrast, free both hands while providing critical information for the user. On the other hand, smartphones now have long battery lives, making it even more difficult for AR glasses to compete.

To make a fully immersive and interactive user experience, environment- and hand-tracking technologies must be further developed; none seem ready yet for mass adoption. While the general public has not yet widely adopted AR glasses, user feedback on near-eye displays suggests screen reprojection in a small form factor is the most wanted feature among the general public.

It took 30 years from their introduction for smartphones to be fully adopted by the public. AR is eight years in—and the hardware is still developing.



Nanfang Yu of Columbia University showed an example of a numerically simulated design that uses stacked metasurfaces etched into a thin film (right) to form compact, see-through AR glasses that reflect information to users at selected narrowband wavelengths while allowing an unobstructed view of broadband real-world light.

S.C. Malek et al., Light Sci. Appl. **11**, 246 (2022); CC-BY 4.0

field of view of 50 to 70 degrees while reducing size. Eye-tracking is required, however, and a difficulty for HOEs on plastic waveguides is ensuring surface parallelism, which requires manufacturing control.

Andreas Georgiou of Reality Optics Ltd., UK, described a waveguide-based VR display architecture. This architecture uses waveguides to illuminate the image-forming optics, enabling dynamic pupil steering. The image is formed using a dynamic hologram illuminated by a steerable Maxwellian arrangement. The holographic nature of the image-forming optics allows for the achievement of full 3D cues and prescription correction.

In this architecture, the usual relationship between field of view and the refractive index of the waveguide is broken, enabling a large field of view with low-refractive-index materials like plastics. This technology's main challenges are developing, recording and mass-producing suitable HOEs with large thicknesses and the need for large-area dynamic holograms.

Future technologies

Another incubator session explored future technologies for creating comfortable AR glasses and VR headsets. Two major directions—leaky-wave metasurfaces and holographic displays—appeared to offer promise toward more comfortable, high-resolution and bright AR/VR devices. Yet there are still challenges to overcome in computational efficiency and form factor for practical implementation.

Leaky-wave metasurfaces. Nanfang Yu (Columbia University, USA) discussed his work combining metasurfaces with guided-wave photonic systems. In these leaky-wave metasurface systems, a guided wave of light traveling across a waveguide outcouples light using nanostructures embedded on the surface of that waveguide. Yu stressed, however, that these structures do not always have to be on the surface; they could also be designed inside a waveguide as periodic pillars.

Such approaches to optical waveguides offer a slim form factor, which can enable waveguides embedded inside classical eyewear. The design and optimization of these structures have parallels with hologram design in computer-generated holography (CGH), but they also account for polarization state and the physical shape of the nanostructures. This makes metasurface design a new research paradigm in computational domains. Metasurfaces still require improvements in efficiency and scattering strength along the waveguide, however. And CGH could benefit from Yu's work by enhancing capabilities such as beam steering (crucial for eyebox formation) and arbitrary beamforming (important for illumination design in holographic displays).

Holographic displays. Suyeon Choi (Stanford University, USA) introduced the research of the Stanford Holographic Display Research Team, focusing on reducing the form factor and improving the image quality of holographic displays.

First, he introduced a novel holographic display architecture that achieves 2.5-mm thickness (albeit with limited achieved image quality). Next, he outlined an algorithmic framework that achieves unprecedented image quality for holographic displays, leveraging

One clear message of the incubator meeting is that there's an abundance of options for light engines and waveguides, and the best combinations are still to be determined.

emerging spatial light modulator (SLM) technology. Choi's team used a piston-mode phase-only SLM that offers new opportunities in phase modulation, offering faster refresh rates in the KHz range. Choi highlighted the fully open-source optimization pipeline, which could enable interactive-rate hologram generation for a fast-paced SLM such as the one used in the Stanford group's research.

What's next?

One clear message of the incubator meeting is that there's an abundance of options for light engines and waveguides, and the best combinations are still to be determined. Clearly, high power efficiency and compact form factor for the light engine are crucial for socially acceptable AR eyewear. During the discussion, however, participants generally agreed that the community may be trying to achieve too many things and support too many use cases at once—and that makes the optical design more challenging. Tailoring designs to targeted use cases may be a better way to go.

In addition, AR cannot be achieved without software and graphics, but most developers work in gaming applications, and the supply of developers capable of creating 3D content—crucial for AR—is limited. More broadly, there is continuous discussion on whether immersive 3D, which imposes a greater cognitive load on users that increases human error, is the right answer. Both hardware and graphical content will, again, depend heavily on the use scenarios. For example, developers rely on eye-tracking information for image rendering and developing gaze-based user interactions. Yet the hardware for eye tracking adds to weight and power consumption.

Incubator participants were asked what they think will be the next steps for making AR glasses viable. Three critical items were brought up: First, we need to understand the market and tailor the need. Second, we need to determine how to achieve more things with minimum hardware. And third, we need to work on content generation and explore special use cases.

Will open source and standardization accelerate the development of augmented reality? Realistically, there seems little or no commercial incentive for sharing among the companies. Open interfaces may be more acceptable from a commercial point of view. However, using the semiconductor industry's development as a reference, an industrial-level AR/VR roadmap may help the industry move forward.

Interestingly, a consortium focusing on laser-scanning-based displays, which was called the LASAR Alliance as of the October 2023 date of the incubator meeting, has since restructured to AR Alliance beginning in 2024, with a variety of leading AR industry companies becoming members. Its mission statement now stresses that it is an "augmented reality hardware development ecosystem" and that one of its goals is to create industry standards.

In the academic world, people find learning about what others are working on beneficial, and they are more likely to share algorithms or tools. Conversation between industry and academia should help move development further. The University of Rochester (USA) has founded an AR/VR NSF Research Traineeship program, inviting industry participation on an external advisory board to facilitate continuous interaction. The program, funded by the US National Science Foundation and industry fellowships, has developed a curriculum that focuses on the basic knowledge required for people who want to work in the field—and on avoiding "engineering myopia" by encouraging interdisciplinary collaboration and curiosity.

"Academia provides a base to experiment without the constraints typically found in an industrial setting," observed Kaan Akşit of University College London. With programs like the one at Rochester, we can look forward to more talent, with engineering empathy, working in the field of AR. OPN

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