Key Challenges to Affordable See Through Wearable Displays: The Missing Link for Mobile AR Mass Deployment

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Abstract:

Low cost see-through technologies for wearable AR displays have been an elusive key element to enable the market for consumer oriented mobile AR. This paper will explore the various available technologies and the key challenges faced in order to develop a platform that will enable affordable wearable displays for the consumer market. The focus is on light guide based see-through technologies for wearable AR displays as this technique is the most promising. The assumption is that form factor, cost, ease of use, and display performance are the major challenges for consumer adoption of wearable AR displays. A comparison of the various technologies and how they relate to these aspects will be made.

Introduction:

The market for augmented reality wearable displays (or AR glasses) is potentially huge. Some estimates say that in the not so distant future, AR glasses could be the user interface of choice and will gradually replace the conventional hand held smart-phone touchscreen interface. The target market therefore is the ubiquitous use of mobile video, navigation, augmented reality, and gaming. Smart-phones are capable of more functionality than ever before and telecoms operators are seeking to increase their non-voice based revenues by offering more services (video on demand, navigation, games, etc.). The major issue is that displays on mobile phones are not large enough (typically 3-4 inches in diagonal) in order to fully enable these new use models. See through wearable AR displays that don't obstruct the user's line of sight allow a non-intrusive, hands free, large screen experience and are therefore a desirable alternative allowing full use of the available computing power of smart devices. Wearable displays are compelling because they offer the ability to display video, navigation, messaging, augmented reality applications, and games on a large virtual screen hands free. However, any such device will need to be affordable and should have a form factor that is attractive enough so that users will easily adopt it. Since users do not "wear" mobile phones, the form factor challenges are different than with a wearable display device. Moreover, the device will need to have enough intelligence built into it in the form of sensors and video processing in order to make it useful for augmented reality, positioning, and gaming applications. If a wearable display device can hit the "sweet spot" of price, performance, and form factor, then it will enable this "hand-free, always-on" revolution. The advent of the wearable display will be nothing less than a new paradigm that will open up a world of possibilities.

Description of various see-through wearable display techniques using waveguides:

Various techniques have existed for some time for See-through video wearable displays. Most of these techniques can be summarized into two main families: "Curved Mirror" based and "Waveguide" based. The curved mirror based techniques use semi-reflective curved mirrors placed in front of the eye with an off-axis optical projection system [1]. These techniques suffer from a high amount of distortion which needs to be corrected optically or electronically adding cost and reducing image resolution. Moreover, certain implementations have a small "eye motion box" which is the equivalent of looking through a keyhole to see the image. This is uncomfortable for the use and requires mechanical adjustment, further adding to cost. The major issue comes from the form factor which is not appealing and handicaps end user adoption (see figure 1 below).

Fig 1: Two curved mirror based wearable AR display technologies (Vuzix on left and Laster on right).

The second family of is the so called “light-guide” or “waveguide” based techniques. These present the most promising technologies for wearable displays since they reduce the cumbersome display optics and electronics in front of the user’s face and in the user’s line of sight. Using a waveguide, the physical display and electronics can be moved to the side (near the user’s temples) and a fully unobstructed view of the world can be achieved, therefore opening up the possibilities to true augmented reality experiences. Various waveguide techniques have existed for some time for see-through wearable displays. These techniques include diffraction optics, holographic optics, polarized optics, and reflective optics.

Waveguide Based Approaches:

Diffractive Waveguide:

The diffractive techniques use deep slanted diffraction gratings (i.e. Nokia technique now licensed to Vuzix and now used by Microsoft for its Hololens project). This technique uses slanted gratings to in-couple collimated light entering the waveguide at a particular angle, then, the light travels through the waveguide using the principle of total internal reflection or “TIR”, and finally, the light is extracted to the eye with another set of slanted gratings [2]. The schematic for this technique can be seen in figure 2 below.

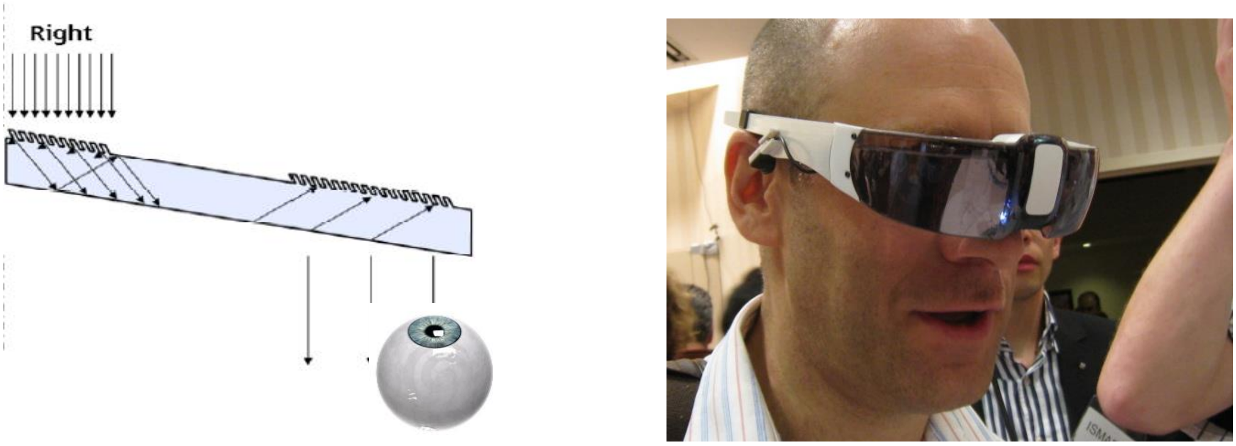


Fig. 2: The schematic for the slanted grating technique invented by Nokia and licensed to Vuzix. An early Nokia prototype based on this principle being worn on the right.

The diffraction grating technique presents some key challenges. The first is producing the deep and slanted Nano-metric grating structures at low cost. The technique for producing these deep slanted structures is not something that is commonplace today in traditional optical component manufacturing. Therefore the technique will remain costly for some time. The second issue with this technique is that it produces color non-uniformity in the image. Since light is in-coupled and out-coupled at a certain angle when it hits the diffraction structure, it creates a “rainbow effect” due to the variation of spectral reflectivity versus the incident angle within the image. This means that the various reflected wavelengths don’t have the same amplitude when they encounter the diffraction pattern at an angle. The diffractive technique therefore works best with monochrome based systems but that is a big limitation for the consumer space where full color is extremely important. The third aspect is that this technology is intrinsically limited in field of view (FOV). Large FOV displays (large virtual screens) are not possible using this technique again due to the variation of spectral reflectivity vs. angle issue. The higher the incidence angle, the higher the color non-uniformity. Higher angles are needed for higher FOV’s and if the FOV is increased beyond 20°, the color non-uniformity becomes very noticeable as the human eye is extremely sensitive the color non-uniformity variations.

Holographic Waveguide:

The holographic technique is quite close to the diffraction grating technique described above with the exception that a holographic element is used to diffract the light [3]. Holograms work by reflecting certain wavelengths of light. In this way, the incident light is reflected at a certain angle with regard to the hologram. Holograms are intrinsically limited when used in a waveguide due to the fact that the reflected light loses intensity with angular variation. Only limited angles are possible in order not to lose too much light and to keep good image uniformity. Therefore, this technique is intrinsically limited in FOV. This technique is also plagued by color issues known as the “rainbow effect”. Holographic elements reflect only one wavelength of light so for full color, three holograms are necessary; one that reflects Red, Green, and Blue respectively. This not only adds cost but since the three holograms need to be “sandwiched” together, each wavelength of the light is slightly diffracted by the other color hologram adding color “cross-talk” in the image. Therefore, the eye sees some color non-uniformity or color bleeding when viewing the virtual image. Some of this color non-uniformity can be corrected electronically but there are limits to this as the human eye is extremely sensitive to this phenomenon. This technique is used by Sony and Konica-Minolta as shown in figure 3 below.

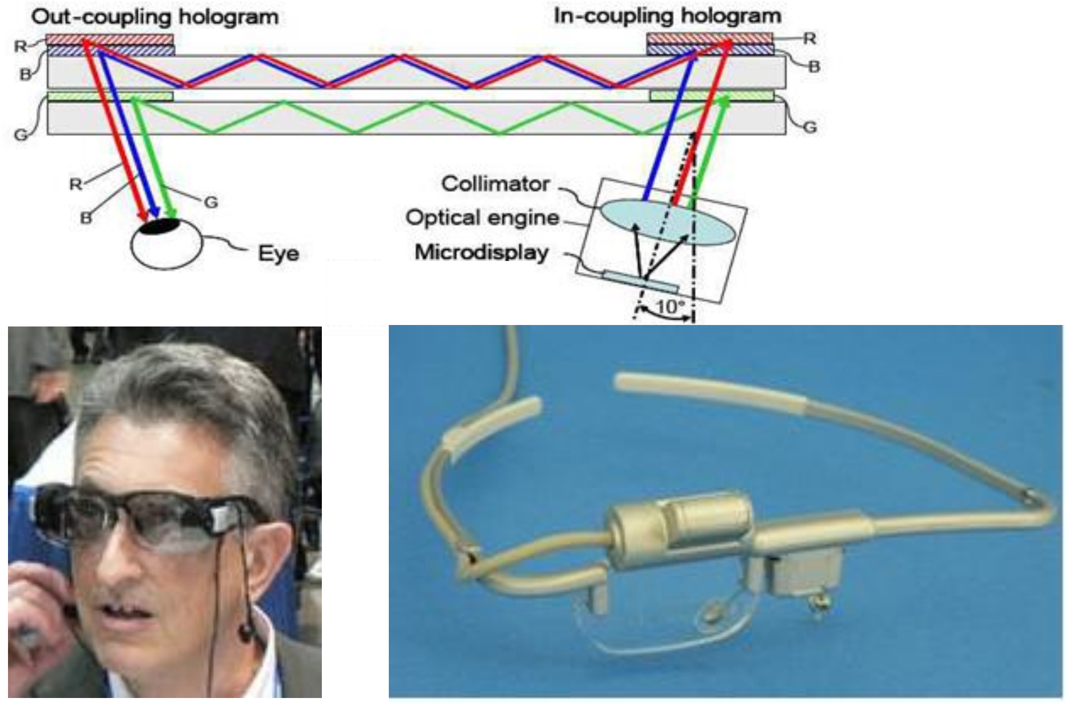


Fig. 3: The schematic above is from a Sony paper written for SID in 2008. Bottom left, Sony prototype. Bottom right, Konica-Minolta prototype.

We have to mention that variations of this technique have emerged recently from some start-up companies (Trulife Optics, UK and Dispelix, Finland). Trulife is working on a new holographic material to increase the index variation necessary for a color display. However, the industrialization of this new material on a large scale still presents a hurdle. Dispelix claims to introduce another diffraction level on top of the device to reduce the rainbow effect that is visible for all these types of technologies. The concept is still a feasibility study. Furthermore, the manufacturability remains to be proven.
Finally, we have to mention that only one product exist today using this technique (Sony) but it uses a a Green Monochrome display.

Polarized Waveguide:
The polarized waveguide technique is used by Lumus. This technique uses multilayer coatings and embedded polarized reflectors in order to extract the light towards the eye pupil [4]. This technology does not suffer from the small FOV issues and the eye motion box can be quite large. However, it suffers from several major drawbacks that do not allow a viable solution for a low cost, consumer based solution. The reflectivity of the polarized reflectors are quite small since it's less than 1/n (n is the number of reflectors). For 6 reflectors used in their current light guide, the reflectivity is around 10%. The polarized coatings are multilayer coatings of 25-30 layers each and must be deposited on glass as plastic is not compatible with this process. Several of these reflectors need to be precisely glued together with extremely tight tolerances on parallelism, cut at an angle (again, with a very high level of parallelism), and polished in order to make the waveguide. Each reflector needs to have a different amount of coatings ranging from 25 to 30 layers in order for the virtual image to be uniform. This process is not geared towards high volume and low cost manufacturing. Furthermore, glass is fragile and the perception of a thin piece of glass in front of the eye will be detrimental to large scale user adoption. Additional drawbacks come from the fact that the system and reflectors are polarized makes the system inherently inefficient because nearly 70% of the light is lost when it is reflected. Moreover, the "rainbow effect" of color non-uniformity exists due to the polarization states. Figure 4 below illustrates this technique and the Lumus prototype.

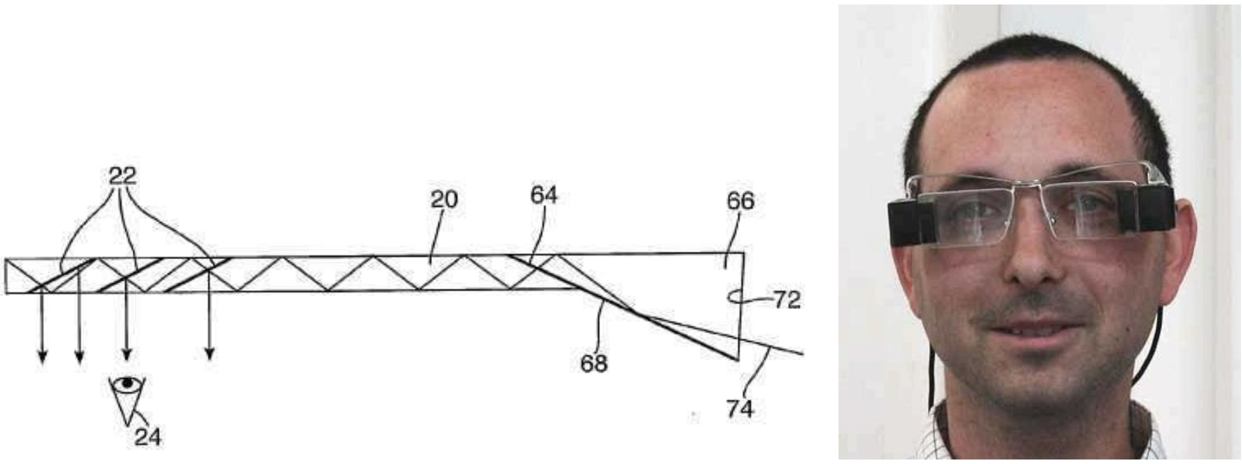
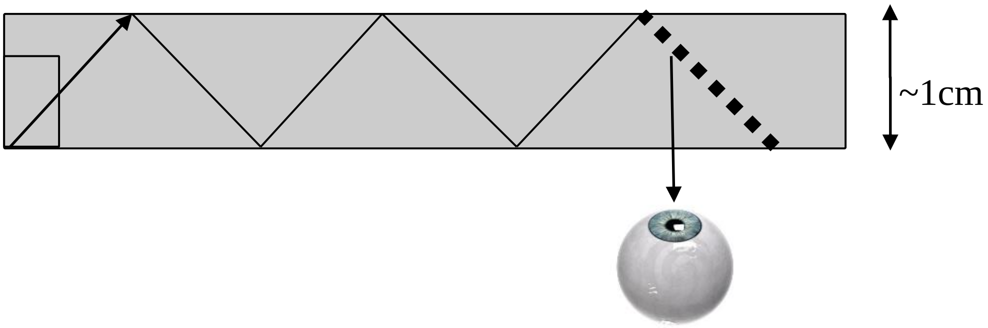


Fig. 4: The schematic from the Lumus patent and the Lumus prototype

Reflective Waveguide:
The reflective technologies have the advantage of using reflective optical components (no exotic components or multilayer coatings). They do not suffer from the color non-uniformity issues since they uses semi reflective mirrors therefore reflecting white light without any degradation. The possibility to use a molded plastic substrate for the light guide is also a key advantage of this technique. As with the other waveguide technologies, an optical collimator magnifies the image generated by a micro display and injects it into the light guide. Through the TIR principle (total internal reflection), the light travels through the light guide and is extracted using a semi reflective mirrored structure using traditional coatings found throughout the optics industry. This will allow the components to be made using traditional coating techniques, therefore reducing cost. Consequently, any type of micro display can be used in this system

since there is no polarization required (LCD, LCOS, OLED). These reflective systems also tend to be more efficient in power consumption because there is no light loss due to polarization or grating/holographic effects. The approach taken by both Epson and Google uses a single reflector embedded into the light guide (although Google implementation does not use TIR). A reflective waveguide is used by Epson in their Moverio product while Google Glass uses a “light pipe” (no TIR technique is used). Other than the lack of innovation, and therefore low entry barrier, the problem with this approach is that the size of the reflector is directly proportional the FOV (Field of View) and eye motion box dimension, therefore the light guide becomes quite thick. In both the Google and Epson cases, the light guide thickness is around 1cm as seen in the figure below. In Google’s case, there is also the additional problem that the light crosses the semi reflective mirror, bounces off a curved surface, and then is again reflected off the mirror towards the eye. This causes additional light losses, therefore making the system much less efficient.
Finally, we should mention that a thick light guide would hinder AR applications fit would introduce a high level of distortion for the see-through vision. That is why the Google Glass display is located in the upper right hand corner of the user’s vision.

Epson Light Guide:



Google Light Pipe:

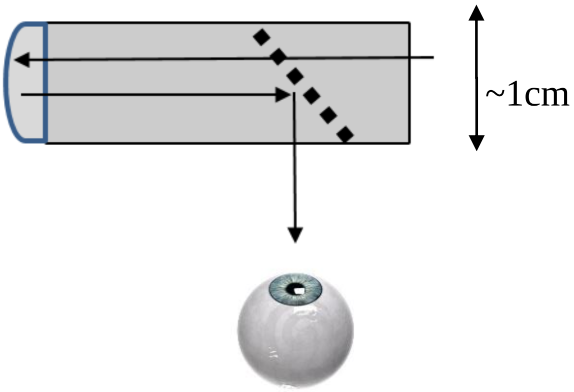


Fig. 5: The single reflector approach of Epson and Google above. Bottom left, the Epson Moviero product. Bottom right, the Google Glass prototype.

Clear-Vu reflective Waveguide:

The Optinvent "Clear-Vu" approach is fundamentally different than the above. Optinvent uses a surface structure made up of several reflecting structures which makes it possible to have a thinner light guide while maintaining a large eye motion box as well as a large FOV. This surface structure allows Optinvent to mould a monolithic light guide (out of one piece of plastic) which is coated with a semi reflective coating. A "cover plate" is glued to this piece of plastic in order to protect the structure and to assure the optical see-through function. This cover plate component does not need to be precise since it is not used to generate the virtual image. It only assures the see-through function by compensating the prismatic effect when the eye pupil looks through the structure of the light guide. The Clear-Vu technology therefore benefits from all the advantages of reflective waveguide techniques (no colour issues, moulded plastic substrate, traditional coatings, better efficiency, large eye box and FOV). Moreover it has the additional benefits of a thinner waveguide made out of one monolithic piece of plastic therefore improving the form factor and further reducing cost. The main challenge of this technology is to mould the light guide and its surface structure precisely and to design a system that finds the right compromise for performance and cost. The schematic below details the Optinvent approach and a prototype using the Clear-Vu system can be seen in the figure below:

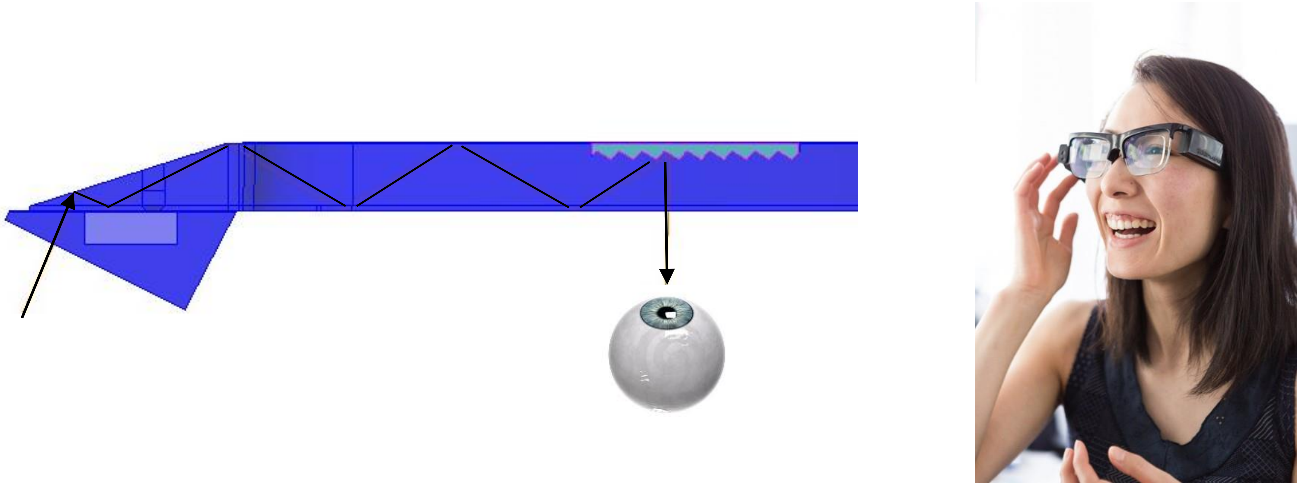


Fig. 6: The surface reflector approach of Optinvent and the "Clear-Vu" prototype.

Conclusions:

Of the various waveguide technologies discussed, the reflective type seems to be the most promising for large scale consumer deployment. The main advantages are the lower cost, plastic substrate, and lack of colour issues. Optical technologies are finally emerging that will enable consumer oriented wearable AR display products to become a reality in the near future.

References:

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[4]: PCT 2006 013565 A1, Lumus patent.