Wedge Optics in Flat Panel Displays

Adrian R. L. Travis, Timothy A. Large, Neil Emerton and Steven N. Bathiche

***Abstract*— Liquid Crystal Display (LCD) technology will struggle to display high resolution on screens as big as whiteboards. Yet there is demand also for less power consumption, three dimensional (3D) images and that the display should be able to see gestures and feel touch. Most of these features are possible with projection and wedge light-guides make projection slim, but pico-projectors are so dim that many will be needed for such a big screen. For now, we use instead a hybrid of technologies: light-guides look out from behind an LCD to see where the viewers' hands and eyes are, and a collimated backlight lets us illuminate one view at a time to each eye. This lets us synthesize 3D with achievable increases in LCD frame rate. We expect that this combination of a multi-view 3D display and a view-dependent rendered image will give us the potential to televise the experience of looking through a window.**

***Index Terms*— display, lens, telepresence, waveguide**

I. Introduction

When the flat panel display was first conceived, most households had only one display, the cathode ray tube, and it had only one purpose, that of watching television. It has taken over four decades to achieve a big, flat, affordable, high definition television display so it is no surprise that the potential uses have changed. Information of many forms besides television has been digitized and the flat panel display has become a general-purpose interface to this information. The flat panel display has enabled new applications such as portable phones and computers, but it has come to act also as something of a brake on these new applications. Silicon chips and hard discs can shrink but displays cannot because people remain the same size, so the flat panel display is taking an ever greater share of the power consumption, weight and cost of an information device [1].

These are familiar challenges but if information technology is the new master, it makes new demands: high definition is no longer enough and the displays on portable phones now feel touch while tabletop displays [2] can see tags placed on top [3]. The more we can learn about the user, the better our chances of guessing their intent so we want also to see which finger has touched, how the hands have moved between touches and what gestures they might have made [4]. Displays are being used also for tele-presence but speakers want to look each other in the face, not see the skewed line of sight delivered by a camera on top of the screen. The display therefore needs to be able to see the viewer as if there were a camera behind the display looking through [5], but what if there is a group of people in front of a screen? Only one of the group can have eye contact with the distant speaker so the rest must each see an image appropriate to their position and this happens to be just what is needed for 3D [6]-[9].

Whatever the new demands of information technology, the appetite for higher resolution persists and there may also still be appetite for greater size. A typical office will have a whiteboard and documents pinned on a noticeboard and if an electronic display is to integrate these functions, it might need laser print resolution on a screen with a diagonal of more than 100”. Even to make a display for high definition television, transparent conductors edged with copper were needed to reach the required data rates [10] and in order to reach the size and resolution of a notice-board, we may need to transmit data optically, just as with telecoms. Optics, in the form of projection, has always been a stratagem for making big displays but projection is bulky. Similarly, one can get only so far by putting a camera behind a screen in order to read tags placed on its surface. Both the conventional metrics of display technology and the new requirements set by information technology would therefore greatly benefit if there were a way of transmitting images via slim light-guides.

II. Wedge Optics

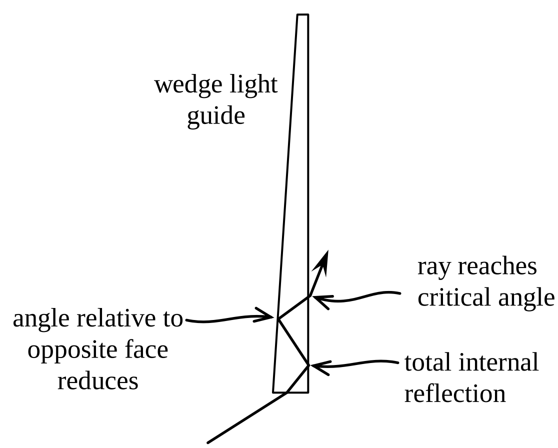

Fig. 1: Each reflection off one face of the wedge reduces the ray’s angle to the other face

Point a ray of light into the thick end of a wedge-shaped light-guide and the ray will propagate towards the thin end by total internal reflection. Each time the ray reflects off one

Manuscript received July 14, 2011. The authors are with the Applied Sciences Group of Microsoft Corporation, One Microsoft Way, Redmond WA 98052 (phone: 425-706-8281, email: adriant@microsoft.com, tlarge@microsoft.com, emerton@microsoft.com, stevieb@microsoft.com)

surface of the wedge, its angle with respect to the normal of the other surface will decrease until the critical angle is reached, at which point the ray will emerge into air [11] (Fig. 1).

The number of reflections required to reach this point will depend on the starting angle of the ray: the greater the difference between this and the critical angle, the greater the number of reflections required to reach the critical angle and therefore the greater the distance to the point of exit, as shown in Fig. 2.

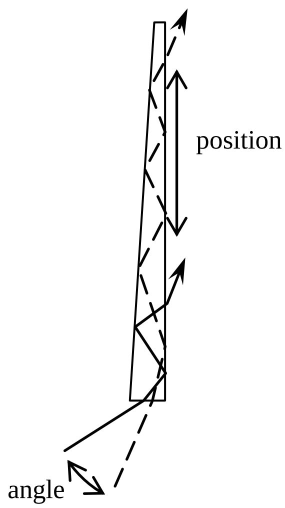

Fig. 2: In a wedge, input angle determines a ray's end position.

The light-guide therefore translates the launch angle of a ray to its on-screen position and this is just what is done by the space between a video projector and the screen to which it is pointed.

If projection is the aim, then rays must expand to fill the width of the screen as well as its height. A simple way to do this is to insert a slab of constant thickness between the projector and the wedge. The length of the slab is set so that once rays have fanned out to the required width, they enter the wedge which stretches the projected image to the required height (Fig. 3).

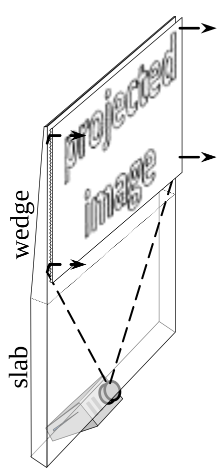

Fig. 3: Insert a slab so rays can fan out to the width of the screen

Rays are in principle as likely to leave from the rear surface of the wedge as from the front so we run the risk of losing part of our image. However, a ray at the critical angle which emerges after no more than one reflection in the wedge will undergo many reflections in the slab, whereas a ray at a shallow angle undergoes many reflections in the wedge but few in the slab. The slab therefore plays a secondary role in making approximately constant the total number of reflections undergone by any ray, with an optimum when the wedge is slightly longer than the slab and is given a slight curve. The projection screen should go next to the exit surface but most projection screens are designed to work best when light is normally incident on their rear. A sheet of prismatic film between the light-guide and screen is therefore desirable so as to turn rays round to the perpendicular and it will often suffice to use the turning film found against the wedge back-light in a liquid crystal display.

Rays must all reach the critical angle before they leave the light-guide so they emerge in parallel. The light-guide is therefore collimating light from a point source and performing one of the basic functions of a lens, its focal point being at the thick end of the wedge. For true collimation across the entire surface, the slab, wedge and turning film should be made rotationally symmetric by extrusion about an axis at the thick end perpendicular to the plane of the slab. However, a lens is more useful if it has a focal plane rather than a focal point, and if the wedge and slab are instead extruded linearly along an axis perpendicular to their cross-section, the thick end becomes a one dimensional focal plane.

It is because this system behaves like a lens that it has the great variety of uses described in this paper. The broad principle is that the light-guide folds up the space between the lens and the point of focus as illustrated in Figs 4 and 5. But the result is not a particularly good lens: instead of the lens of Fig. 5, there is turning film which has facets that cause aperture diffraction just like a Fresnel lens. Furthermore, the critical angle is not 90° as implied by the illustration of Fig. 5 so there is the distortion and astigmatism associated with off-axis systems. The next section will discuss these aberrations and the process of collimation in more detail.

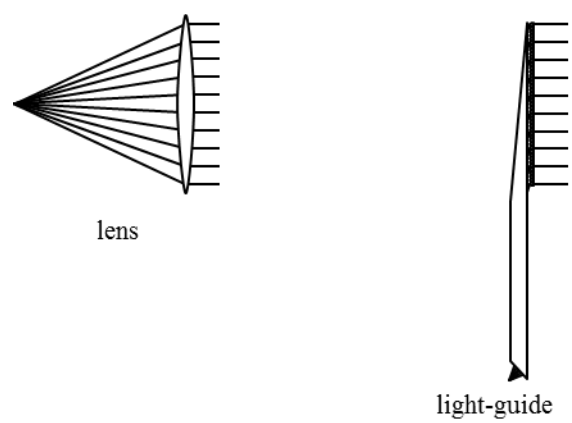

Fig. 4: Rays leave a wedge at the critical angle so all are collimated, as with a lens

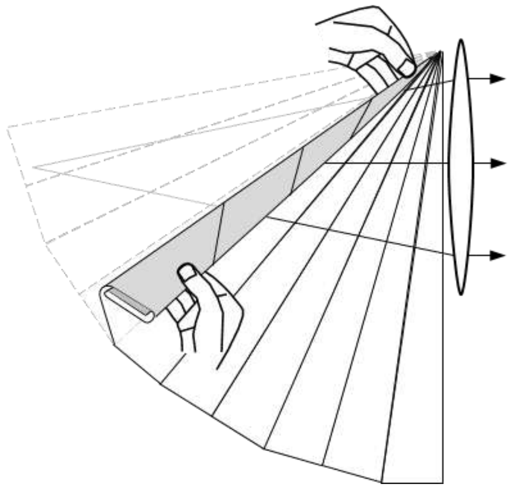

Fig. 5: The light-guide folds up the space between lens and focal plane

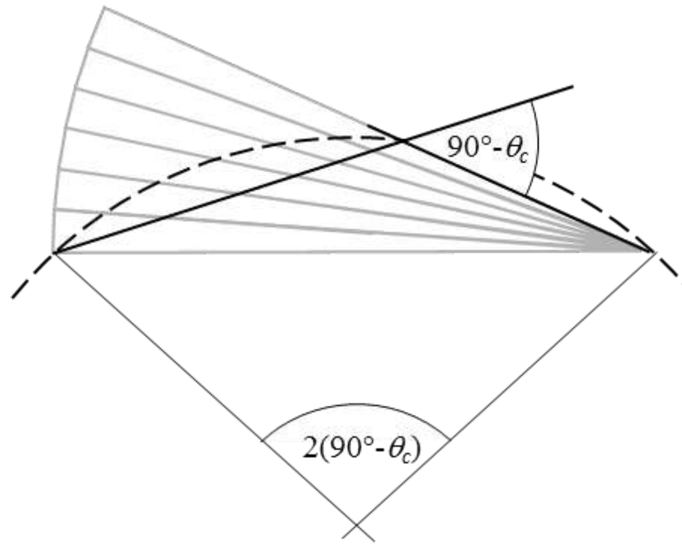

Fig. 7: By the inscribed angle theorem, projection via a thin wedge is like projection inside a cylinder

III. FLAT PANEL PROJECTION

Projectors (and cameras) are simplest if the screen is perpendicular to the axis of projection and the aim is that all points of the screen should be in focus and the projected image should be free of distortion. How does the wedge light-guide compare?

A. Very thin light-guides

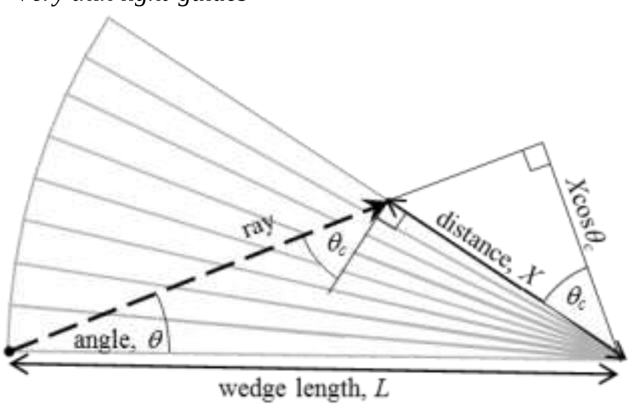

Fig. 6: A ray inside a wedge travels like a straight ray through a stack of wedges

The passage of a ray through a wedge can be found geometrically by tracing a straight line through a stack of wedges as shown in Fig. 6. The ray continues until it crosses one of the surfaces at less than the critical angle at which point the line is terminated because the ray in reality emerges into air. If the wedge is assumed very thin, then the exit angle of the ray approximately equals the critical angle and Fig. 6 shows that:

$$L\sin\theta = X\cos\theta_c \qquad (1)$$

where L is the length of the wedge, θ_c is the critical angle, θ is the starting angle of the ray and X is the distance from the wedge tip to the point where the ray emerges. If θ is small, then it is approximately proportional to X so projection through the light-guide is approximately linear.

The variation of optical path length with angle is shown by the locus of ray exit positions traced in Fig. 7. The locus is an arc centered on a point halfway along the wedge and some distance beneath as determined by the inscribed angle theorem of Euclid [12].

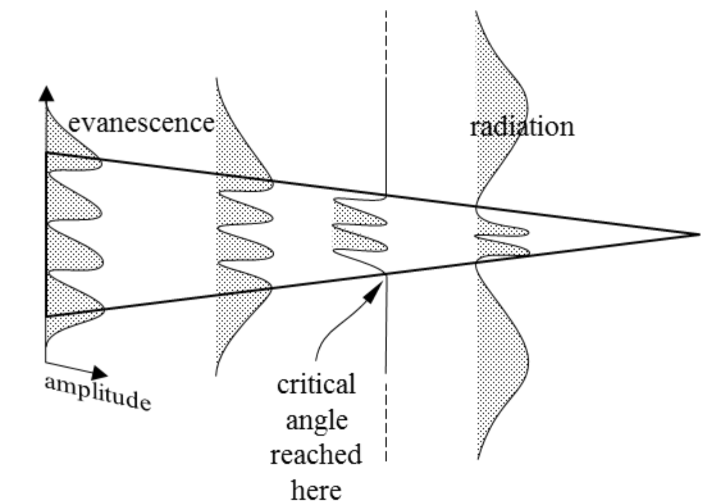

Fig. 8: The peaks of a mode converge like a spring until the critical angle is reached

The light-guide must be thick enough to support as many modes as there are to be pixels on the exit surface. The number of modes in a dielectric slab [13] is $4V/\pi$ where $V = (\pi t/\lambda)(n_{co}^2 - n_{cl}^2)^{1/2}$ so the thickness t of the thick end must be at least:

$$t = \frac{m\lambda}{4\sqrt{{n_{co}}^2 - {n_{cl}}^2}} \qquad (2)$$

where m is the number of pixels, λ is the wavelength of light, n_{co} is the index of the wedge and n_{cl} is the index of its cladding.

However, the pixels produced by such a thin light-guide will not be particularly fine. Instead, as the light-guide tapers, the peaks of the mode will squeeze closer until the field in the cladding switches from evanescence to radiation as shown in Fig. 8. The mode of a slab wave guide can be thought of as a pair of counter propagating rays as shown in Fig. 9 and if we assume that the rear surface is a mirror, the distance p taken for the modal wavefronts to emerge is:

$$p = 2t \tan \theta_c \tag{3}$$

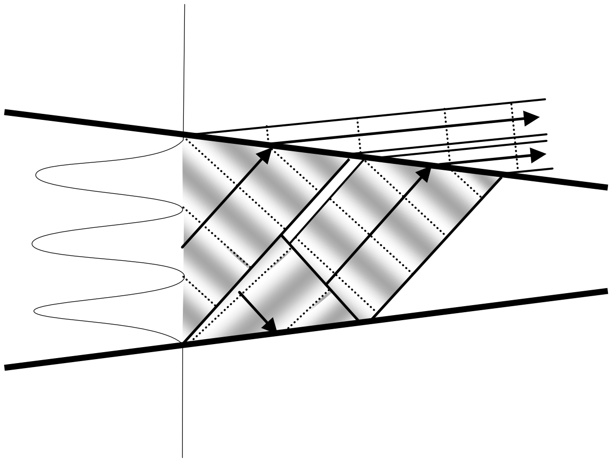

Fig. 9: The mode emerges like a pair of counter-propagating rays

Modes will strip out one by one as the waveguide tapers and if we wish to resolve each pixel, the waveguide must not taper too steeply and the rate of taper is set by the thick end of the waveguide where pixels are thickest. If the rate of taper is too small, however, we run into the problem that some of the light does not emerge in the manner of Fig. 9 but is reflected so as to emerge further along the guide. The result is that a faint duplicate of the projected image appears slightly displaced from the original and we call this duplicate a ghost image.

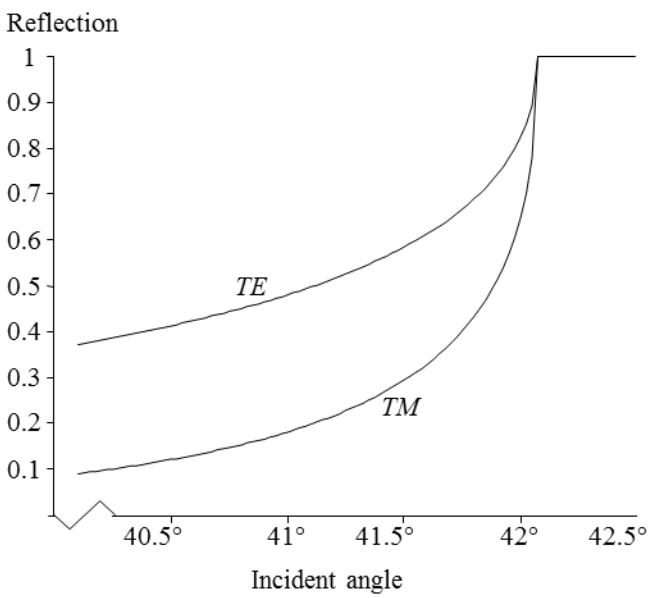

Fig. 10: Predicted fraction of incident light reflected at an uncoated acrylic air interface

Fig. 10 shows what fraction of power is reflected from an uncoated acrylic guide and our problem is that although reflection is total down to the critical angle, transmission is not total thereafter. Instead, some kind of anti-reflection coating is desirable and Fig. 11 shows a prediction of what can be achieved with polarized monochromatic light (wavelength = 0.5 μm, core index = 1.5, cladding index =1.4, first layer index = 2.37, thickness = 0.065 μm, second layer index = 1.44, thickness = 0.37 μm). In practice, the authors have yet to deploy this technique because the ghost is a reflection of a reflection (since the first reflection hits the rear surface) and with TM polarized light, is negligible for basic applications. The reflection of unpolarized white light can nevertheless be mostly cancelled by simple treatments such as, for example, moth-eye coating.

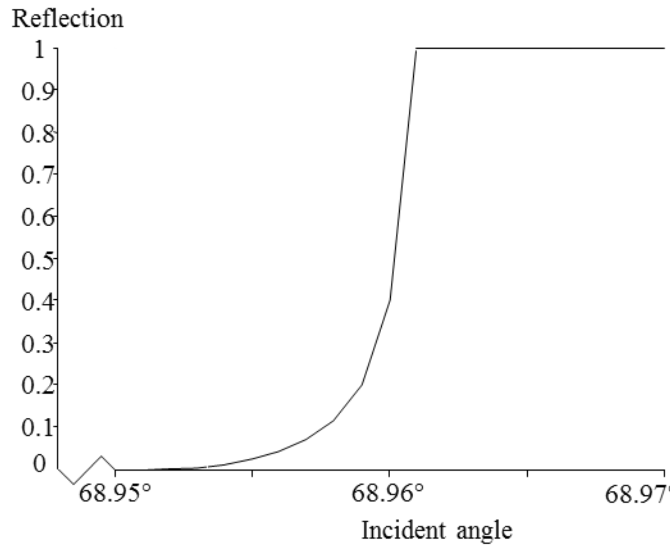

Fig. 11: Predicted fraction of polarized monochromatic light reflected at a dielectric interface with a two layer coating

Figure 12: Photograph of image projected through a wedge of borosilicate glass tapering linearly from 1.5 mm to 0.5 mm over a distance of 200 mm

Fig. 12 shows the result when an image illuminated by a laser of wavelength 532 nm was projected through a glass wedge made by polishing a flat on borosilicate float glass waxed to a slightly tilted base. 3M TRAF II turning film was placed against the wedge surface with a slight space beneath and a diffuser on top.

B. *Light-guides of finite thickness*

A very thin light-guide has insufficient étendue to collect the light from an incoherently illuminated projector and even with coherent illumination, strategies to eliminate speckle tend to increase étendue. Within a thicker light-guide, rays must be focused in order to get the finest pixels possible but a ray which leaves near the tip will have travelled much further than one which leaves near the thick end. The insertion of a slab between the projector and wedge improves matters somewhat and the passage of a ray through a slab and wedge can be found geometrically by tracing a straight line through a stack of slabs then a stack of wedges as shown in the diagram of Fig. 13.

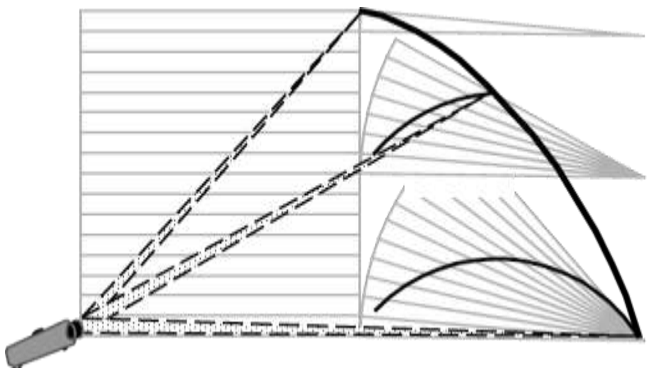

Fig. 13: Optical path length through a slab plus wedge varies little with ray input angle

The stack of wedges must be shifted up or down, depending on the point at which the ray leaves the stack of slabs, and our locus of exit points equates to a line drawn to an arc via one end of its horizontal chord. The distance to point of exit now varies with injection angle much less than for a wedge alone and the locus of points curves inwards slightly.

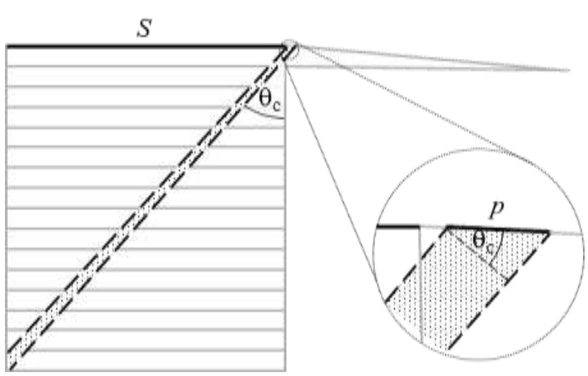

Fig. 14: A pixel can be smaller than the light-guide thickness if a ray bundle is convergent.

Once a light-guide is thick enough for focus to be necessary, its minimum thickness depends on how fine the projected pixels must be. The entrance of the light-guide must be thick enough to pass whatever diameter ray is needed to achieve the required resolution at the exit surface. Simplest first is to consider a ray launched approximately at the critical angle and the ray diameter D_0 at exit will equal the pixel diameter $p\cos\theta_c$ as shown in Fig. 14. The angle of concentration of a focusing beam [14] equals $4\lambda/n\pi D_0$ where λ/n is the wavelength in glass of refractive index n, and the optical path length back to the point of entry equals $S/\sin\theta_c$. It follows that at the point of entry, the diameter D of the ray bundle must be:

$$D = Sn\frac{4\lambda/n}{\pi}\frac{1}{p\cos\theta_c} \tag{4}$$

The actual thickness of the light-guide depends on what angle of bevel is chosen at the input but a good compromise is a bevel such that the thickness equals D, i.e.

$$t \approx 1.7\frac{S\lambda}{p} \tag{5}$$

For a resolution of 250 μm through a slab of length 1 meter, we can aim for a thickness of 3.8 mm.

Fig. 13 evades the question of what happens when a ray bundle hits the kink between the slab and the wedge. If the slab and wedge were to be very thin, the kink would be imperceptible and the thick ends of the wedge would stack into a smooth curve. This smooth curve is like the surface of a lens so that parallel horizontal rays drawn through the stack of slabs would be concentrated to a point at the tip of the wedge. This gives us a hint of how the light-guide behaves but the concept of focus is only useful if the light-guide is somewhat thick so consider instead the diagram of Fig. 15. The paths of rays folded by total internal reflection can be unrolled in the manner of Fig. 15 onto a flat plane but not without breaks so the geometry of the unfolded system is non-Euclidean and illustrated in Fig. 16.

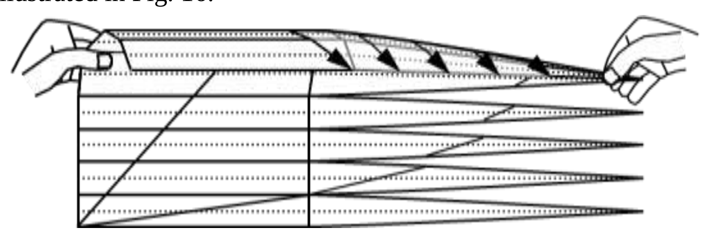

Fig. 15: The path of rays through a slab then wedge cannot be unfolded onto a flat plane without breaks

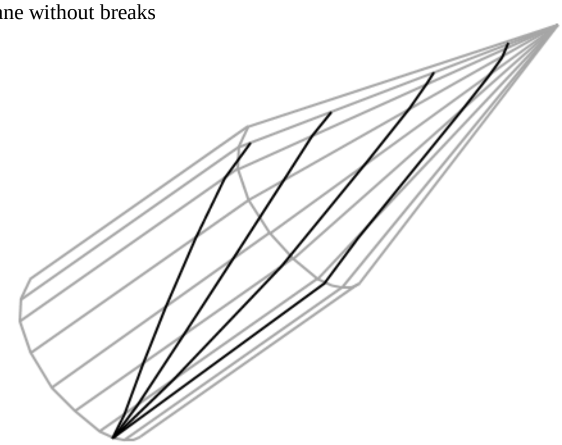

Fig. 16: The path of rays through a slab then wedge can be unfolded onto a curved surface

If the light-guides were very thin, the surface would be smooth. Otherwise, the surface is faceted like that of a pencil, but we can assume that the path of each ray is not greatly different between the faceted and smooth cases. In that case, the ray bundle should behave as if it has passed through a lens whose focal length equals L, the length of the wedge: does it?

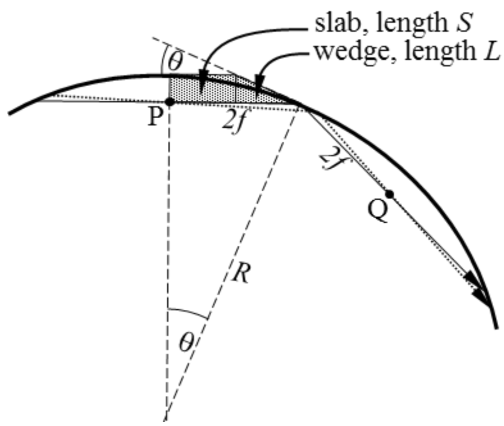

Fig. 17: The kink between slab and wedge smooths into a curve (thick line) which collimates rays from a point at the input

Consider rays reflecting only once off the surface of the wedge/slab. This is the worst case so let us make the transition region cover the whole of the wedge plus slab as shown in Fig. 17 by the thick curve. Fig. 17 shows by symmetry that rays from entrance P which reflect near the wedge's tip form an image at Q. The entrance is halfway along a chord, and the focal length f of the curve is a quarter the length of this chord, i.e. $\frac{1}{2}(L + S)$ which approximately equals L if $L \approx S$. So if rays reflect off the side at the curved boundary between wedge and slab, they should be focused at infinity when they leave the projection lens, the same as for the very thin case.

When rays travel at such a shallow angle, they may of course miss the kink entirely in which case the bundle will not be focused at all and this alternation between rays which are unfocused and those which are focused can produce bands in the image projected near the tip of the wedge. In reality, it is impractical for a wedge to taper all the way to the tip so the bands are less severe than they might be. Nevertheless, the curvature of the transition region is cylindrical so it introduces astigmatism.

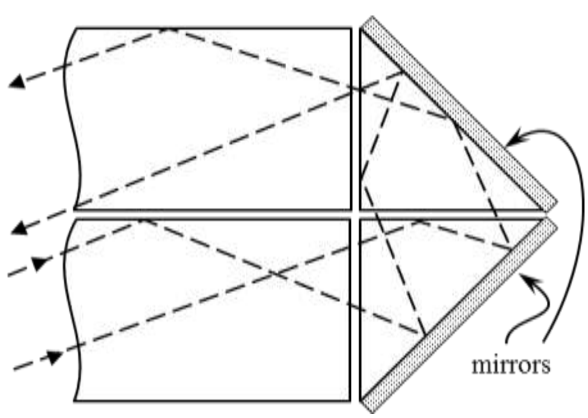

Fig. 18: A pair of prisms can fold a light-guide but not easily

The picture on a display should fill the screen but when a projector is pointed into a slab and wedge light-guide, no picture emerges from the slab. In principle, one can fold the slab behind the wedge using a pair of right-angled prisms as shown in Fig. 18 but in practice this is difficult. The prisms should be made of polymer in order that their thermal expansion coefficient matches that of the acrylic and they should be spaced by a low index layer in order that rays guide round the fold in the manner of Fig. 18. Few polymers have indices lower than 1.30 so the prisms must have an index of at least 1.71 and although polymers with such high indices exist, they are thermosets. Thermosets tend to shrink when cast so it is difficult to make prisms with the necessary accuracy. Experiments with glass prisms have shown that an extra subtle problem is that acrylic sheet tends to have a center with a very slightly higher index than its surfaces. This does not matter to a ray which zig-zags from side to side but it becomes apparent when the plastic is interfaced to truly homogenous glass. Lastly, there is the problem that a fold can only be inserted where both surfaces of the wedge are flat. The transition region is curved so it must either go before the fold or after, and it becomes increasingly difficult to fit the transition region into either the slab or the wedge as its size increases for the reasons given in the preceding paragraph.

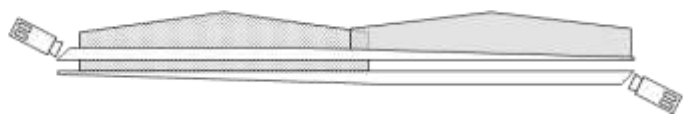

Fig. 19: An anti-parallel pair of wedge light-guides will project images which overlap

The price of projectors continues to fall and an alternative would be to place two light-guides anti-parallel so that the picture projected from one wedge fills the space left by the slab of the other as shown in Fig. 19. This is a form of tiling which is rarely successful with active matrix displays but tiling works much better with projection because the projected images can be made to overlap and blend gradually from one to the other. Such a system would free us from the challenge of making folding prisms but how difficult is it to make the wedges themselves?

IV. FABRICATION

Three factors need attention when making a wedge: thickness profile, smoothness and transparency. It may seem that the most difficult of these is the thickness profile, after all, a ray may reflect dozens of times, perhaps even hundreds between entrance and exit and angular errors are notoriously prone to accumulate. However, the propagation of light through a light-guide is not like a series of cannonades in billiards where the slightest angular error is magnified by successive collisions. Instead, the Lagrange invariant, i.e. the conservation of numerical aperture, étendue or brightness, requires that

$$t \sin\theta \quad = constant \tag{6}$$

where t is the thickness of the light-guide and θ is ray angle. This means that if the thickness of the light-guide is slightly different from that specified at one point, behavior at the rest of the light-guide will be unaffected provided that the bump or dip is gentle. It also gives us a simple way of determining approximately where a ray leaves a light-guide. For a ray launched at angle θ_0 into a guide whose starting thickness is t_0 then the ray will leave when guide thickness equals t_c where:

$$t_c \sin\theta_c \quad = t_0 \sin\theta_0 \tag{7}$$

We can think of t_c as the critical thickness for a ray, and the light-guide surfaces can undulate at random provided that the thickness is greater than t_c until that point where the ray is to emerge. Errors in thickness therefore translate directly to errors in pixel position, so if our target is that the projected image have a distortion of less than 1%, then the thickness of the light-guide at any point must deviate by no more than 1% from specification. This happens to be approximately equal to the shrinkage of plastic as it leaves an injection molding machine whereas if the light-guide is to be machined with a 1 mm thick slab, the thickness tolerance is 10 μm. Many machine tools are accurate to this tolerance if well maintained.

Once the wedge profile has been machined, it must be made much smoother than standard optical surfaces because the ray reflects of the surface so many times. The residual roughness will partially scatter a ray and the total integrated scatter (*TIS*) off an opaque surface is given by [15]:

$$TIS \quad = \left(\frac{4\pi\sigma\cos\theta_i}{\lambda}\right)^2 \tag{8}$$

where σ is the root-mean-square roughness, θ_i is the angle of incidence and λ is the wavelength. Many ray-tracing programs use this equation also for a dielectric interface and it is a good approximation but the index difference across the interface has an effect. The rigorous analysis is too long for inclusion in this paper but a good target is that the surfaces should have a roughness average of 1 nm or less. It should be emphasized that this is a specification for roughness, not flatness, and there is no need for the surfaces to be especially flat because curvature on one side of a light-guide is all but cancelled out by equal curvature on the other. Nevertheless, glass optical components are typically polished to a smoothness of 2 or 3 nm and plastics, being soft, are more difficult to polish than glass.

It is astonishingly fortunate that cast acrylic, which is the most transparent off-the-shelf sheet, is also so affordable, so easily machined and so smooth. The smoothness arises because the sheet is usually formed by polymerizing the monomer between sheets of float glass which themselves typically have a roughness of as little as 0.1 nm because they are the frozen surface of a liquid. The un-machined surface therefore needs no further treatment, indeed it is important that the protective film be left on this surface until the last possible moment. As for the machined surface, a simple way to make it smooth is to lay on a thin piece of acrylic sheet then inject index-matching fluid into the gap and roll out the excess. Index-matching glues can also be used but many create haze by attacking the surface. Fig. 20 shows a photograph of an image from a video projector with an arc-light source being projected through an acrylic light-guide which tapers from a thickness of 25 mm to 12 mm.

Fig. 20: Image projected via a 25 mm thick acrylic light-guide

Off-the-shelf acrylic sheet typically loses light at a rate of 10% per meter which makes the material much more transparent than any float glass. This would be a tolerable figure if all the light were absorbed but some is scattered and scatter degrades the contrast of a projected image which is a crucial contributor to image quality. Distilled acrylic can have a loss of less than 2% per meter [16] and even lower figures have been quoted [17], [18] but there is no large scale source of such clear acrylic at present. The projection of images through wedges may therefore only be competitive after a significant investment in the manufacture of purer material and this seems a heavy task if the aim is to do no more than replace the liquid crystal display. However, wedge light-guides can enhance a liquid crystal display, a key enhancement being that they can give a display the ability to see.

V. Flat Panel Periscope

It is a basic principle of optics that the path of rays can be reversed so it comes as no surprise to learn that a wedge light-guide can be used to capture images instead of project them. This interests designers of the user interface who want a camera that can look out from a display as if from a position some distance behind [5]. The aim is that the camera should be able to watch a hand approach all the way from afar until it touches the screen so that, for example, the interface can tell not only that it has been touched but by which finger of whose hand. This concept of looking out from a display is also needed for video-conferencing. In a classic video conference between, say, Jack and Jill, he sees her via a camera at the edge of her display so although she is looking at Jack's picture on her screen, it appears to Jack that she is not. Speakers tend not to stare at each other during natural conversation but important messages are signaled by when eye contact takes place and for how long and the lack of eye contact is at least one good reason why video-conferencing has yet to become commonplace.

Alternatives to light-guides have been tried, for example one can scatter cameras around the edge of a flat panel display and interpolate the view in between [19], [20] but this is hard because we are so perceptive to where eyes are looking. A second approach is to have a displayed-sized array of cameras [21] which might be put behind a transparent display but cost aside, the cameras would need enormous depth of field to detect both touch and distant objects. Photo-sensors have been integrated into the backplane of LCDs [22], [23] but without lenses these detect only shadow and a lens small enough to fit between the pixels of a LCD is little better than a pin-hole camera. The LCD itself can be used as a mask like that of an X-ray telescope [24] but again, the resolution is limited by pin-hole diffraction

Instead, reverse the rays in the diagram of Fig. 4 and the result is a device where a conventional video camera pointed into the thick end of the wedge light-guide forms an image of anything placed against its exit surface. This captures an image of anything placed on the surface of the screen as if it were a photocopier, i.e. the kind of image needed for Microsoft Surface. Suppose, however, that someone removes the diffuser and alters the focal power of the camera lens so that it is focused at infinity. The light-guide and turning film are now acting like a large Fresnel lens in the manner of Fig. 21, and the camera at the thick end can in principle focus on objects in front of the screen provided that they are not too far away. If the aim really is to make the system operate like a window, then a negative Fresnel lens could be placed in front of the turning film or else integrated with it so as to cancel the focal power of the wedge.

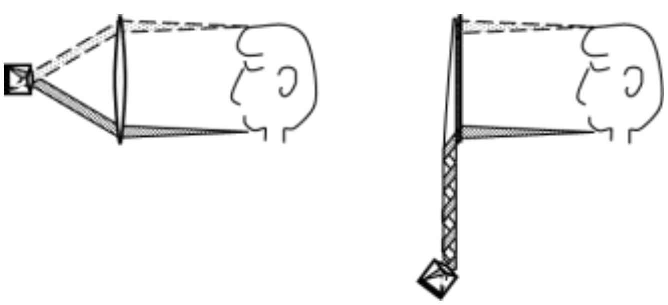

Fig. 21 Imaging through a wedge light guide is like imaging through a lens.

When a wedge light-guide is used in this way as a periscope, scatter has little effect because there is such a low chance of rays being scattered into something as small as the pupil of the camera. Indeed, if the light-guides are to be used only for user input, defects of all kinds are more tolerable because the final image is not seen by any user and it is moderately easy to make panels which capture images good enough for the machine vision algorithms to work. Sandwich the light-guides with a liquid crystal display and one can combine the excellent image quality of a LCD with the image capture properties of the wedge light-guide. However, the details of this are challenging and there are many choices to be made.

A wedge light-guide captures an image only from half its area, with the thicker half being used merely to allow rays to fan into the camera. The problem is the same as for projection and once again, it seems simplest to have two anti-parallel wedges, each with its own camera. The image-capturing part of one wedge looks through the fan-in region of the other and the result is a pair of images which must be stitched together to cover the whole surface. The design of algorithms which stitch the images requires care but is considerably easier than, for example, designing algorithms which interpolate between images from different points of view.

The wedge light-guides are transparent so they could in principle go in front of the liquid crystal display but users like the LCD image to be as close to the surface of the display as possible. The wedge light-guide therefore typically goes behind but liquid crystal displays transmit barely 6% of visible light and only slightly more at infra-red wavelengths. There follows a struggle to design a system which gets enough light from objects in front of the LCD back to the cameras. We want reasonably uniform illumination of the objects of course but this is exactly what is not produced by the spatially modulated emission of a display, a particular problem if the object is placed on the screen. Infra-red images are good enough for the user/computer interface but infra-red illumination is needed which must not dazzle the cameras. Back-lights and turning films can both be made at least partially transparent so there are many options but care must be taken not to diminish the great uniformity now expected on the backlight of a modern liquid crystal display. Photographs of images captured through wedge light guides are shown in Figs. 22-25.

Look through a bare wedge light-guide with the naked eye and the image of objects placed on the surface seems almost faultless, but the images of Figs. 22-25 are not as good as can be captured by a camera through free space. An important problem is that not enough light gets back to the camera so its aperture must be increased and it receives more scatter from the light-guide which degrades contrast. Also, camera lenses are designed to correct the flat field seen in free space, not the astigmatism and varying depth of field seen through a wedge light-guide, whereas the focus of a naked eye continually

Fig. 22: A hand in front of the screen, imaging at infra-red wavelengths with a wedge camera through an LCD

Fig. 23: A hand touching the screen, imaging at infra-red wavelengths with a wedge camera through an LCD (uses a leaky front light diffuser)

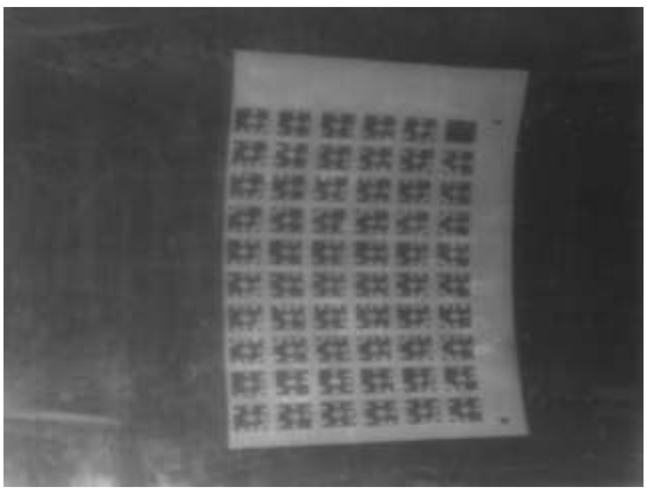

Fig. 24: tags laid against the screen, imaged at infra-red wavelengths

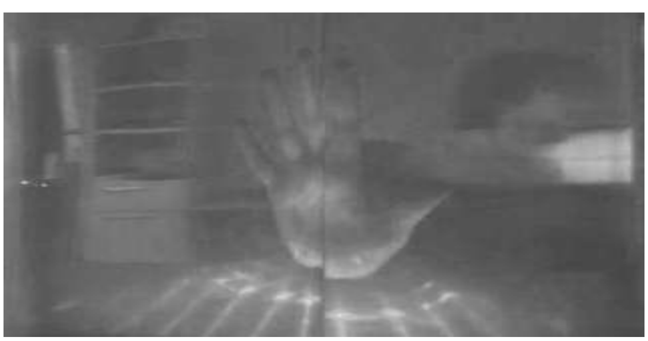

Fig. 25: Detection at visible wavelengths through a transparent OLED using a pair of Wedge cameras. The center vertical line is the stitch-line between the two wedges

adjusts as its center of attention roves across a picture. The images of objects placed some distance away from the screen are even poorer and although much of this may be due to uncorrected astigmatism, a more fundamental problem is aperture diffraction.

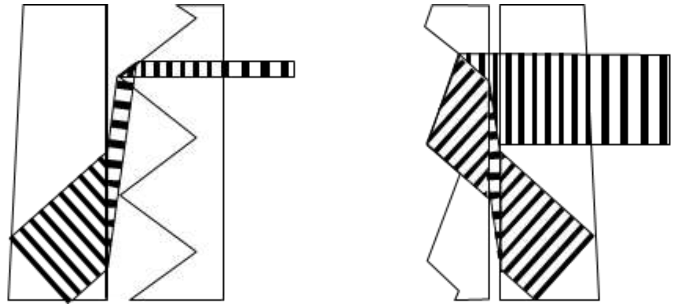

Fig. 26: Two kinds of turning film

The critical angle varies with wavelength in acrylic which can blur color images. Furthermore, if we use the turning film found in the light-guide of a conventional liquid crystal display as shown on the left of Fig. 26, the ray bundle reflects off only the tip of a prism which itself may have a pitch as small as 30 μm. The aperture imposed on the ray bundle can be as small as 3 μm which introduces enormous aperture diffraction that blurs any kind of off-screen image. Instead, we use the prismatic film on the right of Fig. 26 where light emerges into air at the same angle whatever its wavelength and the facets are larger versus pitch so aperture diffraction is reduced. Light is redirected through the wedge so both surfaces should ideally receive anti-reflection coatings which may add to cost. Aperture diffraction could be further reduced by increasing the pitch of the prisms but if the prisms become too coarse, we cannot resolve fine detail on objects placed against the screen. The requirements of on-screen and distant objects are contrary and the equation governing resolution is:

$$\sin\theta = \frac{\lambda}{d} \tag{9}$$

A typical camera has a field of view of 30° and 1000 pixels per row so each pixel resolves half a milliradian. If a wedge panel is to get the same resolution at a wavelength of 500 nm, then the size of the facets of the turning film must be 1 mm. This is too big for the ¼ mm pixel of a typical notebook display or 25 μm pixel of a laser printer but approximately equals the size of a pixel on a 42” LCD. There remains the potential for Moiré fringing between the turning film and the pixels of the LCD but turning films are easily modified and one can imagine schemes which combine the benefits of both fine and coarse prisms. A less tractable problem is aperture diffraction caused by the LCD itself.

It can be useful to think of an LCD as the video equivalent of the slide on an overhead projector but LCD’s are much less transparent and covered by pixel features which give rise to aperture diffraction. The LCD pixels are divided into red, green and blue sub-pixels each a third the width of the pixel itself, and the width is further reduced by the opaque transistor and storage capacitor which can occupy almost half the area of the sub-pixel. Even on a 42” display, we can expect a resolution of no more than 200 pixels from a camera with a 30° field of view and much less from smaller displays. This adds to the existing problems of LCD fragility and parallax between the plane of the LCD and the plane of the wedge. Other flat panel display technologies such as OLED can also be made transparent but they also need an active matrix and even if transparent metal oxide transistors are used, there would still be structure on the display due to the need to create red, green and blue sub-pixels.

It is therefore tempting to look again at the prospects of projecting an image through a wedge and with economies of scale, one can imagine refining acrylic to eliminate scatter. We might choose to make a flat panel version of Microsoft Surface by placing camera and projector side by side at the thick end of each wedge – the slight difference in alignment has no effect. If the top surface is a diffuser, only fingers which actually touch the surface are clear to the camera. Diffusers can be thick and plastic so this approach is more robust than with a LCD. Furthermore, the projector can focus onto the diffuser so that there is no mismatch between the captured and displayed image and the latter appears on top as preferred by most users.

However, we could instead arrange that the diffuser operates only on light from the projector and is clear to light en route to the cameras so they can image off-screen objects in the manner of Fig. 21. Most ambitiously of all, we could limit the angular spread of the diffuser and place many cameras and small projectors at the thick ends of each wedge so as to capture and create 3D images. This may indeed be the best approach for wall-sized displays since one is then free of the size and resolution constraints imposed by use of a LCD. But LCD's have unique advantages besides that of being the dominant display technology and wedge light-guides may help resolve the problem of aperture diffraction from the color filters.

VI. FLAT PANEL FLASHLIGHT

The first LCD's were monochrome hence efficient enough to need no backlight and it was largely the introduction of color filters that caused the backlight to become a key component of the LCD. Both color filters and the fact that light is everywhere created then selectively blocked make LCD's wasteful of light so it was important that light be created as efficiently as possible. The fluorescent lamp is marvelously efficient but its emission is diffuse and white and this places further constraints on the choice of liquid crystal material and filter spectral width which exacerbate the waste of light. Nevertheless, the currents needed to modulate the pixels are independent of the brightness of the image and so much less than the currents needed in emissive displays that the LCD can be at least as efficient [25].

If liquid crystals are designed around the light source, then matters change with the arrival of new light sources. Fluorescent lamps are linear or area sources because the charge needs space to accelerate but arc lights are point sources and, being of comparable efficiency to fluorescents, made possible the video projector [26]. Arcs are hot so are contained by a delicate glass globe thicker than most flat panel displays but light emitting diodes work best when cool. Light emitting diodes are still rarely as efficient as arc lamps but have improved so much that they are beginning to be used in video projectors [27]. The first light emitting diodes to be used in backlights were a mixture of red, green and blue, introduced in order to increase the color gamut of the display [28]. Later, backlights were made where the light emitting diodes were switched off behind areas of the LCD where the image was intended to be dark in order to improve contrast [29]. However, even when LED's from one batch are measured and sorted, there remain variations in the emission spectrum from one LED to another and the spectra change over time. One can correct the color co-ordinates of a color trio of LED's by monitoring their emission and varying the drive currents but this is an expensive process and color LED's are in any case more expensive than white LED's.

It is white LED's which are now becoming common-place in LED backlights [30] and this is because the mercury in fluorescent lamps is no longer acceptable in a flat panel display. At first, many LED's were needed to replace one fluorescent lamp but costs reduce if the number of components is kept to a minimum so LED manufacturers have continually increased the number of lumens per device. This has led to a new problem: wedge-shaped light-guides have long been used to smear the emission from a fluorescent tube across the back of a LCD but if the source comprises a few LED's, hot spots appear. Scattering sites can be added, but surface features scatter light at different intensities to different directions whereas Titanium Oxide particles are difficult to place with any precision during the molding process. One approach has been to place the LED at the thin end of a wedge so that rays fan out and reflect off the thick end then adjust scattering sites so that the sum of scatter from the forward and reflected rays is uniform [31]. However, all these approaches see the low étendue of a spot source of light as the problem and scattering as the solution, whereas low étendue is surely an opportunity and any kind of scattering is a waste of this opportunity [32].

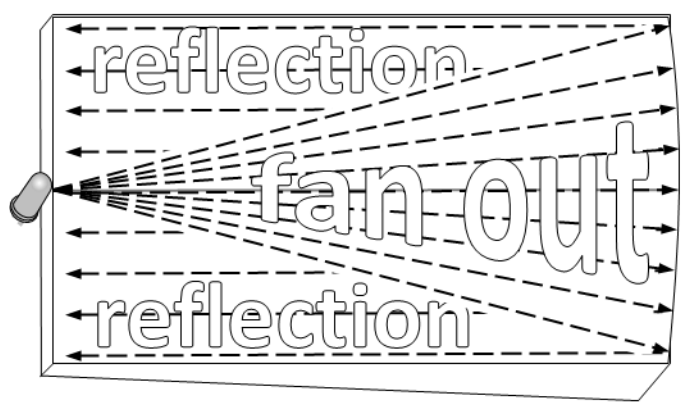

Fig. 27: rays fan out and reflect of the think end which is curved to as to collimate them.

The wedge light-guide of Fig. 27 allows rays to fan-out so as to illuminate the exit surface uniformly and in parallel, as if from a light bulb through free space via a Fresnel lens onto a wall. We can indeed eliminate the fan-out region by placing the light source at the thin end of the wedge and allowing it to reflect off the thick end but without further change, the rays will return to the thin end without leaving the waveguide. Instead consider first our aim, that rays should hit the whole of the exit surface in parallel with uniform intensity, and trace these rays backwards through the system. We wish that the rays should emanate from a point and Fig. 27 shows that from a view perpendicular to the plane of the light-guide, the thick end should have a radius of curvature equal to half the length of the light-guide.

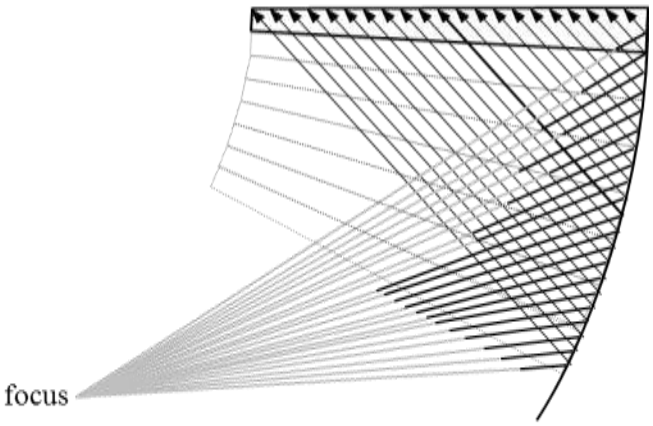

Fig. 28: We want all rays to exit at the critical angle. Trace them backwards and reflect off the thick ends

Fig. 28 shows a cross-section of the light-guide with rays hitting the final interface at the critical angle since this is how they emerge. Tracing the rays backwards, we draw them as straight lines through a stack of wedges in the manner of figure 6 but note that the thick ends of this stack join to form something like a curve. When parallel rays reflect off a curve, they concentrate to a point so we can focus the rays by giving the thick end a radius of curvature equal to twice the length of the wedge, i.e. the thick end is a section of a sphere. The rays drawn in Fig. 28 will, after reflection off the thick ends, converge to a notional point as shown but none of them will reach it because they will reach the critical angle beforehand and cease to be guided. Instead, reduce the angle of the reflected rays by embossing the thick end with facets as shown in Fig. 29 which slew the point of focus around to a position where a ray from the center of the exit surface is reflected parallel to the plane of the wedge (shown as a thick ray).

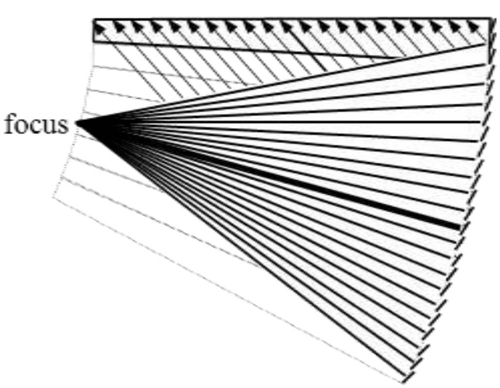

Figure 29: Emboss the thick end with facets to reduce ray angle and guide rays to focus

According to Fig. 29, all the rays will be guided to the thin end but Fig. 29 is inaccurate: each wedge is a mirror image of that above and below so we cannot have the prisms all oriented as shown. Instead, we emboss the thick end with the zig-zag prisms shown in Fig. 30.

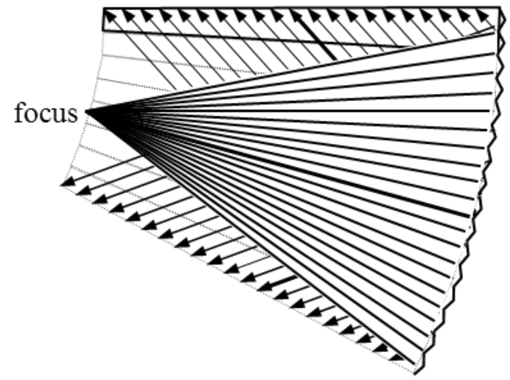

Fig. 30: By symmetry, the facets must be a zig-zag so rays exit from top and bottom

A zig-zag structure has reflective symmetry in the center plane of the wedge but half of the rays traced back from the exit surface will be reflected out of the system. However, let us now return to reality with the rays emanating from a point at the thin end and when they reflect off the thick end, half will be reflected so as to emerge from the upper surface of the wedge and half from the lower surface. It is then a simple matter to place a mirror against the bottom surface so that all emerge from the top with uniform intensity and in parallel.

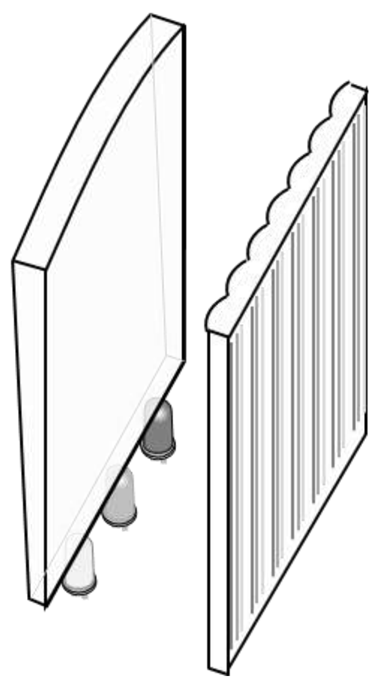

Fig. 31: The guide collimates light from each LED and the lenslets concentrate light through the appropriate color filter.

A basic advantage of this set-up is that light from each LED at the thin end is spread across the whole of the exit surface with moderately good uniformity. It follows that if there are red, green and blue LED's at the thin end, there is no need to measure and balance color co-ordinates. A more important advantage of this light-guide is that it acts as a lens. The rays from each LED emerge in parallel and we put an array of cylindrical lenslets behind the LCD with one lenslet per red/blue/green triad of color filters as shown in Fig. 31. The position of the LEDs can be adjusted so that each lenslet concentrates red light through the red filter, green light through the green filter and blue through blue. This reduces the power consumption by a factor of almost three and perhaps more if the light were to be concentrated through each filter so as to avoid the opaque circuitry at its periphery as shown in Fig. 32.

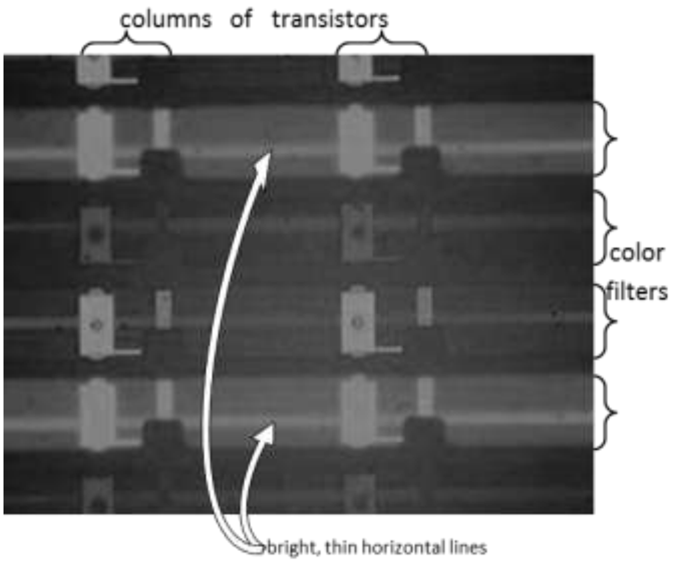

Fig. 32: Photograph showing light (the bright, thin horizontal lines) being concentrated through the center of each color filter.

Of course this means that there may no longer be any need for color filters but the benefit here is not only one of less cost. Color filters are the major cause of aperture diffraction with images seen through an LCD and that caused by transistors is much less. Perhaps with the extra mobility and therefore smaller size of metal oxide transistors, we might be able to reduce aperture diffraction to an acceptable level.

Instead of (or as well as) adding an array of cylindrical lenslets, we could instead place a Fresnel lens between the wedge light-guide and the LCD so that rays from each LED are not collimated but focused to a point as shown in figure 33. It is easy to forget that an eye sees an image because rays of light travel from the image to the eye so if the eye is at the point where the rays focus, it will see the image on the LCD. All other rays - except those going to other eyes - are wasted power so by concentrating the light from our LEDs into the viewer’s eyes, we reduce the waste of light by a large factor. An often-cited advantage of OLEDs versus LCDs is that light is only created where it is needed, but once the light has been created, an OLED has no control where the light goes. The opposite happens when light through an LCD is concentrated into the eye but the gains may be greater. The average brightness of a video is typically 20% of peak white whereas the eyes looking at a screen are a much smaller fraction of the solid angle of a hemisphere. Viewers move of course, so we need both a way of tracking heads and secondly a way of scanning the illumination so that it follows the head.

The introduction notes that many of the new demands being made on displays are driven by the demands of information

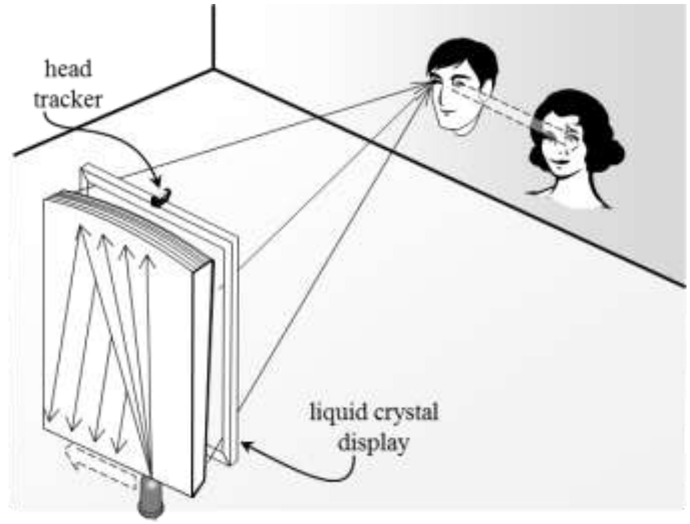

Fig. 33: Rays through the liquid crystal display are concentrated to each eye in turn found by the head tracker

technology but information technology is also a new resource. Machine recognition has recently undergone a major advance, the cost of computing power and data storage having reduced to the extent that moderately simple algorithms suffice to get powerful results. The recognition of speech, handwriting and people has improved so much that heads can now be tracked well enough that failures are few and brief. As for scanning our illumination, the wedge light-guide acts as a lens so the point to which rays are concentrated can be moved simply by moving the LED. The thin end of the wedge is effectively one dimensional but heads tend to move from side to side more than up and down so we add a vertical diffuser and a line of LED’s along the thin end of the wedge. Fig. 34 is a photograph of the image formed on a screen in front of a wedge backlight with a Fresnel lens against its exit surface and nine LEDs at its thin end. We see that the LEDs are imaged so well that we can easily concentrate light into each eye and this implies that we have a backlight which can enable 3D [33] aside from the aberrations at wide fields of view noted in the next section.

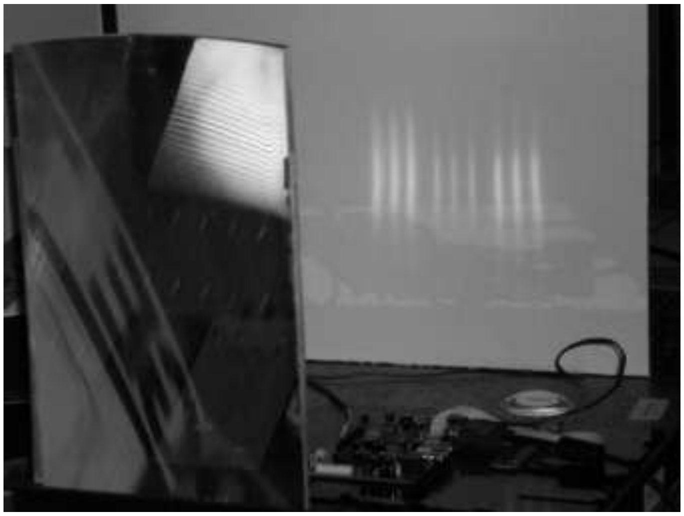

Fig. 34: Photograph of the image formed on a screen in front of a wedge backlight with a Fresnel lens against its exit surface and nine LEDs at its thin end.

VII. 3D AND TELEPRESENCE

The ideal of tele-presence, shown in Fig. 35, is a window where a ray entering the front surface emerges with the same position and direction from the rear, and vice versa, even though both surfaces have been separated far apart by some imaginary saw. The only rays which matter are those which end up in eyes and Section V has explained how to detect rays incident on a screen en route to a point some distance behind whereas Section VI has explained how to illuminate an LCD with rays which concentrate into an eye. Arrange for the relative positions of the eye and the point behind the screen to coincide and it remains to put the appropriate picture on the LCD, at least as far as that eye is concerned. There will of course be at least one other eye looking at the screen so we must repeat the exercise for that eye and any others. How well can all this be done?

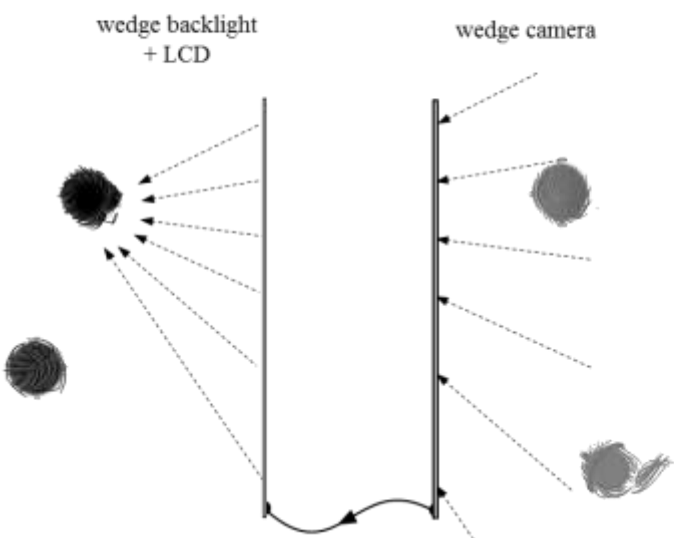

Fig. 35: A wedge camera and wedge backlight have the potential to televise the experience of looking through a window

LCDs are now available which display alternately each of a stereo pair of views that are made visible to each eye in turn by a pair of spectacles whose eye-pieces switch between opaque and transparent. LCD frame rates have already reached 240 Hz and rates approaching 1 kHz have been reported [34], [35]. In many cases, the aim is to display color-sequential video but we think the frame rate would be much better used for 3D. There are other ways of creating 3D of course and lenticular arrays are particularly popular. However, the key is not to degrade rays passing through the display en route to the wedge periscope and a collimated backlight has the advantage of adding no structure to the display.

Great effort has gone into making conventional LCDs with fields of view well in excess of 120° and many stratagems for 3D struggle to do so well. This is because lens aberration increases non-linearly with angle to the lens axis and wedge light-guides, being a form of lens, are no exception. However, the consequences of aberration are less serious in a collimated backlight than in a lenslet and to a considerable extent, can be

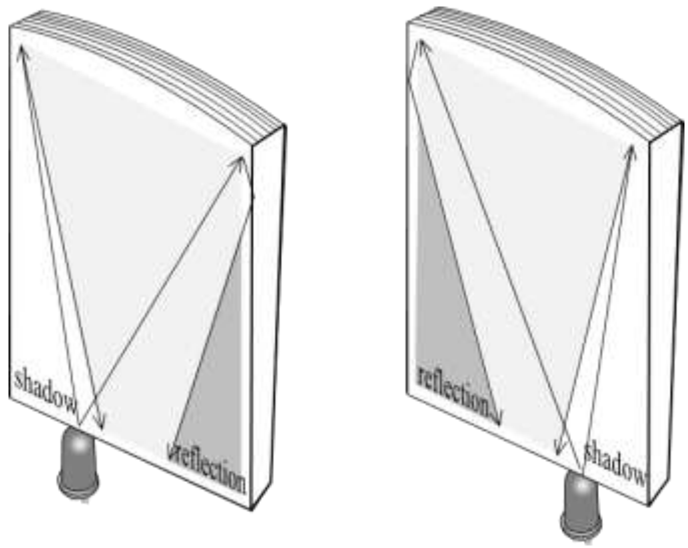

Fig. 36: The shadow left by one LED can be filled by its equidistant opposite from the centerline

corrected by software. What cannot be corrected by software is the shadows left at one or other thin corner of the wedge backlight when off-center LEDs are illuminated, as shown in Fig. 36. The solution here looks to be to illuminate a pair of LEDs equidistant from the center of the thin end so as to fill one another's shadows.

Viewers move not only side to side but also forward and back whereas the Fresnel lens in front of the collimated backlight concentrates rays to a point on a plane. A liquid crystal lens is a possibility but it may be possible to manage variable depths also by structured lighting.

A wedge light-guide used as a periscope will also introduce aberrations at large angles to the perpendicular but the aberrations will not matter provided that they can be corrected by computer. The difficulty of doing this should not be underestimated so we can expect quality to be poorer at extreme angles but this may be acceptable since the area subtended by the screen to the eye is so much smaller.

VIII. CONCLUSIONS

The space otherwise needed between a lens and its focal plane can be folded by total internal reflection into a wedge-shaped light-guide with rays deflected to or from the critical angle by an array of prisms. Such a lens light-guide may be a key component if flat panel displays are to televise the experience of looking through a window. We have used the light-guide as a backlight to make the image on a liquid crystal display visible to one eye at a time. We have used the light-guide as a periscope to capture images on or in front of the screen as if from a point deep behind where the remote eye would be if in situ. Machine vision can both recognize commands made by touch and gesture and track the eyes of each viewer so that the appropriate image may be captured on the remote screen and displayed to the related eye on the local screen.

We have used the system to display 3D without the need for spectacles and the backlight draws a fraction of the power needed when the illumination is diffuse. Power consumption therefore need not constrain the size of liquid crystal displays which may affordably increase with the elimination of color filters made possible by structured color illumination. Nevertheless, for wall-sized images it may prove simplest to do without a liquid crystal display altogether and project images through the light-guides.

The minimum thickness of the light-guide is that needed to resolve on-screen pixels of the required size without blurring due to aperture diffraction. The resolution of off-screen pixels is further limited by aperture diffraction through the facets of the prismatic film and through the opaque grid of the active matrix array. Lens aberration occurs at wide angles to the screen perpendicular and powerful image processing may be needed both to correct images captured at extreme angles and to display them to individual eyes at extreme angles. The projection of high contrast images will require material with less scatter than that of typical acrylic sheet.

IX. ACKNOWLEDGMENTS

The authors would like to thank F. Payne for suggesting the recipe of figure 11 and help with calculations on surface roughness, and J. E. Carroll for his continual encouragement.

X. REFERENCES

[1] H. Kawamoto, “The history of liquid-crystal displays”, *Proc. of the IEEE*, vol. 90, no. 4, pp. 460-500, Apr. 2002.

[2] S. Izadi, S. Hodges, S. Taylor, D. Rosenfeld, N. Villar, A. Butler, and J. Westhues, “Going beyond the display: a surface technology with an electronically switchable diffuser.” In *Proc. 21st annu. ACM symp. on User interface software and technology*, pp. 269–278, Oct. 2008.

[3] P. H. Dietz and B. D. Eidelson, “SurfaceWare: dynamic tagging for Microsoft Surface.” In *Proc. 3rd Int. Conf. on Tangible and Embedded Interaction*, pp. 249-254, Feb. 2009.

[4] J. Underkoffler, B. Ullmer, and H. Ishii, “Emancipated pixels: real-world graphics in the luminous room,” In *Proc. 26th annu. conf. on Computer graphics and interactive techniques*, pp. 385-392 , Aug. 1999.

[5] A. D. Wilson, “TouchLight: An imaging touch screen and display for gesture-based interaction.” In *Proc. 6th Int’l. Conf. on Multimodal Interfaces*, pp. 69–76, Oct. 2004.

[6] H. Baker and Z. Li, “Camera and projector arrays for immersive 3D video.” In *Proc. 2nd Int. Conf. on Immersive Telecommunications*, Article 23, May 2009.

[7] W. Matusik and H. Pfister, “3D TV: a scalable system for real-time acquisition, transmission, and autostereoscopic display of dynamic scenes.” *ACM Transactions on Graphics SIGGRAPH*, vol. 23, no. 3, pp. 814–824 , Aug. 2004.

[8] D. T. Nguyen and J. F. Canny, “MultiView: improving trust in group video conferencing through spatial faithfulness.” In *Proc. 2007 SIGCHI Conf. on Human Factors in Computing Systems*, pp. 1465–1474 , 2007.

[9] Y. Taguchi, T. Koike, K. Takahashi, and T. Naemura, “TransCAIP: a live 3D TV system using a camera array and an integral photography display with interactive control of viewing parameters”, *IEEE Trans. Vis. Comp. Graph.*, vol. 15, no. 5, pp.841-852 , Sep./Oct. 2009.

[10] H. C. Choi, S. G. Hong, B. H. Lim, S. W. Lee, and S. D. Yeo, “Development of a 30-in. wide-QXGA+ TFT-LCD for high-information-content displays”, In *SID Int. Symp. Digest of Technical Papers*, vol. 35, pp. 119-121, May 2004.

[11] A. Travis, F. Payne, J. Zhong, and J. Moore, "Flat panel display using projection within a wedge-shaped waveguide", *SID International Display Research Conference*, vol. 20, pp. 292-295, 2000.

[12] R. Fenn, “Geometry”, Springer 2003 p. 81

[13] A. Snyder and J. Love, “Optical Waveguide Theory,” Chapman and Hall 1983 pp. 704 and 227

[14] E. Hecht, “Optics” 4th edition, Addison Wesley, 2002

[15] J. C. Stover, “Optical Scattering Measurement and Analysis “, McGraw-Hill, p. 86, 1990.

[16] F. G. H. Van Duijnhoven, “Gradient refractive index polymers produced in a centrifugal field: preparation, characterisation and properties”, Doctoral thesis, Technische Universiteit Eindhoven, 1999.

[17] Y. Koike, S. Matsuoka, and H. E. Bair, “Origin of excess light scattering in Poly(methyl methacrylate)”, *Macromolecules*, vol. 25, no. 18, pp. 4807-4815, Sep. 1992.

[18] N. Tanio, Y. Koike, and Y. Ohtsuka, “Temperature dependence of light scattering by low-loss Poly(methyl methacrylate) glasses”, *Polymer Journal*, vol. 21, no. 2, pp. 119 -125 , 1989.

[19] B. Stenger, T. Woodley, T. K. Kim, and R. Cipolla, “A vision-based system for display interaction.” In *Proc. 23rd BCS Conference on Human-Computer Interaction*, pp. 163-168, Sep. 2009.

[20] G. D. Morrison, “A camera-based input device for large interactive displays.” *IEEE Computer Graphics and Applications*, vol. 25, no. 4, pp. 52-57, July-Aug. 2005.

[21] J. Tanida, T. Kumagai, K. Yamada, S. Miyatake, K. Ishida, T. Morimoto, N. Kondou, D. Miyazaki, and Y. Ichioka, “Thin Observation Module by Bound Optics (TOMBO): concept and experimental verification.” *Appl. Opt.*, vol. 40, pp. 1806-1813 , 2001.

[22] W. Den Boer, A. Abileah, P. Green, T. Larsson, S. Robinson, and T. Nguyen, “Active matrix LCD with integrated optical touch screen.” In *SID Int. Symp. Digest of Technical Papers*, vol. 34, pp. 1494-1497, May 2003.

[23] C. J. Brown, H. Kato, K. Maeda, and B. Hadwen. "A continuous-grain silicon-system LCD with optical input function" *IEEE Journal of Solid-State Circuits*, vol. 42, no. 12, pp. 2904-2912, Dec. 2007.

[24] M. Hirsch, D. Lanman, H. Holtzman, and R. Raskar. "BiDi screen: A thin, depth-sensing LCD for 3D interaction using lights fields" *ACM Trans. Graph.* vol. 28, no. 5, pp. 1-9, Dec. 2009.

[25] M. Hack, M. S. Weaver, J. J. Brown, L.-H. Chang, C.-K. Wu, and Y.-H. Lin, “AMLCD and AMOLEDs: how do they compare for green energy efficiency?” In *SID Int. Symp. Digest of Technical Papers*, vol. 41, pp. 894-897, May 2010.

[26] G. Derra, H. Moench, E. Fischer, H. Giese, U. Hechtfischer, G. Heusler, A. Koerber, U. Niemann, F-C. Noertemann, P. Pekarski, J. Pollmann-Retsch, A. Ritz, and U. Weichmann, “UHP lamp systems for projection applications”, *Journal of Physics D: Applied Physics*, vol. 38, no. 17, pp. 2995-3010 , Sep. 2005.

[27] F. Fournier and J. Rolland, “Design methodology for high brightness projectors”, *Jnl of Display Technology*, vol. 4, pp. 86-91, Apr. 2008.

[28] H. Sugiura, H. Kaneko, S. Kagawa, M. Ozawa, H. Tanizoe, H. Katou, T. Kimura, and H. Ueno, “Wide color gamut and high brightness assured by the support of LED backlighting in WUXGA LCD monitor”, In *SID Int. Symp. Digest of Technical Papers*, vol. 35, pp. 1230-1233, May 2004.

[29] T. Shirai, S. Shimizukawa, T. Shiga, S. Mikoshiba, and K. Käläntär, “RGB-LED Backlights for LCD-TVs with 0D, 1D, and 2D Adaptive Dimming”, In *SID Int. Symp. Digest of Technical Papers*, vol. 37, pp.1520-1523, June 2006.

[30] W. Schwedler and F. Nguyen, “LED Backlighting for LCD TVs”, In *SID Int. Symp. Digest of Technical Papers*, vol. 41, pp. 1091-1096, May 2010.

[31] K. Käläntär, S.F. Matsumoto, T. Katoh, and T. Mizuno, “Backlight unit with double-surface light emission using a single micro-structured light-guide plate”, *Journal of the SID*, vol. 12, pp. 379-387, 2004.

[32] A. Travis, T. Large, N. Emerton, and S. Bathiche, "Collimated light from a waveguide for a display backlight," *Opt. Express*, vol. 17, pp. 19714-19719 , Oct. 2009.

[33] A. R. L. Travis, "Autostereoscopic 3-D display", *Applied Optics*, vol. 29, pp. 4341-4343, Oct. 1990.

[34] N. Koshida, Y. Dogen, E. Imaizumi, A. Nakano, and A. Mochizuki, “An over 500 Hz frame rate drivable PSS-LCD: its basic performance” In *SID Int. Symp. Digest of Technical Papers*, vol. 40, pp. 669-672, Jun. 2009.

[35] Y. Hirakata, D. Kubota, A. Yamashita, H. Miyake, M. Hayakawa, J. Koyama, S. Yamazaki, K. Okazaki, R. Sato, T. Cho, K. Tochibayashi, and M. Sakakura, “A 6-inch field sequential blue phase mode LCD with integrated driver using oxide semiconductor” In *SID Int. Symp. Digest of Technical Papers*, vol. 42, pp. 32-35, May 2011.

Adrian R. L. Travis has a Bachelor of Arts and Doctorate of Philosophy in Engineering from Perterhouse, Cambridge.

He is a Researcher with the Applied Sciences Group at Microsoft, Redmond, WA. Before joining Microsoft, he spent his entire career as a lecturer at the Engineering Department in Cambridge University.

Dr. Travis is a fellow of the Royal Academy of Engineering, of the IET and of Clare College, Cambridge.

Timothy A. Large holds a Bachelor of Arts in Natural Sciences with a specialization in Physics from Christ’s College, Cambridge.

He is a Researcher with the Applied Sciences Group at Microsoft, Redmond, WA. Before joining Microsoft, he ran a small consulting business specializing in optical systems and component design. The company worked on displays, sensors, spectrometers, lighting systems and adaptive optics. Prior to that, he worked for and Nortel Networks and The Technology Partnership. While at Nortel, he lead a team that adapted landline systems for use on long-distance repeater-less 10GBit links, including systems he helped design for the north English Channel, the Irish Sea, the Philippines and Taiwan. He has authored over 20 patents. His current research interest is the application of imaging light-guide technology to interactive displays.

Mr Large is a member of the SID and SPIE.

Steven N. Bathiche is the Director of Research in Microsoft Corp.'s Applied Sciences Group, which he helped establish. He obtained his Bachelor's degree in Electrical Engineering from Virginia Tech and a Master's degree in Bioengineering from the University of Washington. While in graduate school, he developed the Mothmobile, a hybrid robot that uses an insect as its control system via a neural electrical interface.

He has been doing applied research at Microsoft since 1999 and was the inventor of a number of Microsoft features and products, including the SideWinder Freestyle Pro game pad, the first commercial gaming device to use accelerometers. He oversaw a complete redesign of the pointer ballistics algorithm that has been shipping in Windows since XP, and he invented the new laser tracking technology in Microsoft pointing devices. He also is the co-inventor of Microsoft Surface.

His interests are in creating novel human interfaces and computer form factors that create new scenarios and user paradigms to ultimately affect people's lives and their digital world. His current technical focus is in the field of co-locating display and sensing technologies. He holds 45 patents.