# Collimated light from a waveguide for a display backlight

**Adrian Travis,[1,2*] Tim Large, [2] Neil Emerton, [2] and Steven Bathiche [2]**

[1] *Clare College, University of Cambridge, Trinity Lane, CB2 1TL, UK*
[2]*Microsoft Corporation, One Microsoft Way, Redmond, WA 98052-6399, USA*
**arlt1@cam.ac.uk*

**Abstract:** We report light collimation from a point source without the space normally needed for fan-out. Rays emerge uniformly from all parts of the surface of a blunt wedge light-guide when a point source of light is placed at the thin end and the source's position determines ray direction in the manner of a lens. A lenticular array between this light-guide and a liquid crystal panel guides light from color light-emitting diodes to designated sub-pixels thereby removing the need for color filters and halving power consumption but we foresee much greater power economies and wider application.



**OCIS codes:** (110.2945) Illumination design; (230.7390) Waveguides, planar; (080.3630) Lenses; (080.4298) Non-imaging optics.

## References and links

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## 1. Introduction

Space is conventionally needed between a lens and its focal plane in order that rays from a point source can fan out before undergoing collimation. We therefore expect devices such as car headlights or solar concentrators to be bulky but it was explained recently how to fold the fan-out space into a wedge-shaped waveguide by directing the point source into its thick end [1]. Here we explain how to go one step further by directing the source into the thin end so that collimated rays emerge from all parts of the wedge surface with no blank margins. Lenses have many uses but the authors have concentrated on liquid crystal display backlights.

Wedge-shaped waveguides are commonly used to spread light from a fluorescent tube across the rear of a liquid crystal display and the guides are filled with diffusive particles in order that the illumination be uniform. The liquid crystal panels rarely transmit more than 4% of this light, the field of view is often wider than the users would ideally like and the backlight comprises almost half the cost of the liquid crystal display [2]. The standard fluorescent lamps contain mercury so they are rapidly being replaced by light emitting diodes but these are point

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sources of light rather than area sources of light which makes it harder to get uniformity. Many light emitting diodes are needed along the edge of the light-guide if there are not to be peaks of brightness near the light emitting diodes and such a large number of components adds to the expense [3].

The size of liquid crystal displays continually grows and a display with a 42” diagonal can consume at least 100 W [4]. Visionaries talk of wall-sized displays but it is surely unacceptable to have such large displays in every home while their power consumption remains so high. Plasma displays and organic light emitting diode displays have the advantage that they emit light only where it is needed, but their disadvantage is that power must flow along thin conductors which, in a liquid crystal panel, need only transmit signals so for most images there is little improvement in efficiency.

The power consumption of a liquid crystal display can be decreased by a factor of at least three if the wedge backlight is swapped for a two dimensional array of light emitting diodes which are switched off behind areas of the liquid crystal panel where it is intended that the image be black [5,6]. However, no two light emitting diodes are exactly alike and eyes are sufficiently sensitive to non-uniformity that even light emitting diodes manufactured under stringent conditions must be measured and sorted into bins of equivalent color.

The color filters in a liquid crystal display are expensive and waste approximately two thirds of the light, e.g. the red filter rejects blue light and green light etc. Illuminate one at a time with red, then green, then blue light emitting diodes and this loss can be eliminated provided that the liquid crystal panel switches sufficiently quickly. However, the cathode ray technology on which modern display standards are still based has the color constituents of each pixel recorded simultaneously and if they are displayed other than simultaneously, the edges of moving images look like rainbows [7].

We adopt the strategy [8] of reducing power without binning or rainbows by using our light guide to spread the emission from each light emitting diode across the entire screen then imaging it through one set of color filters (red, green or blue).

## 2. Principle

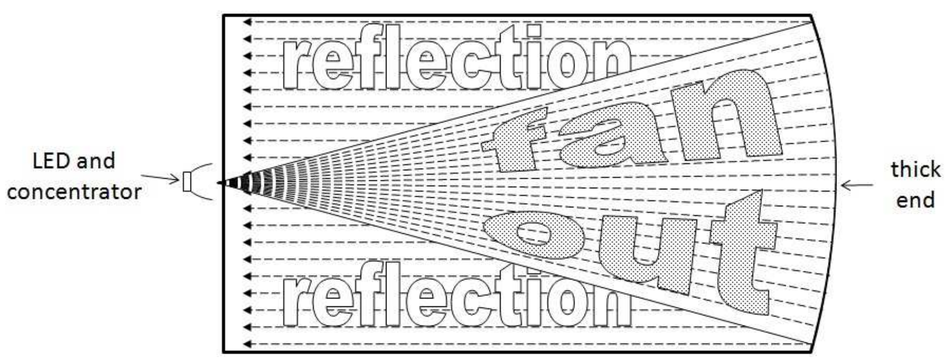


Fig. 1. Plan view: rays fan out to the thick end where they are reflected in parallel.

Place a point source of light at the thin end of a blunt wedge waveguide and rays of light will be confined within the two planes of the waveguide surfaces but will fan out within those planes as shown in the plan view of Fig. 1. At the thick end, rays reflect off a mirror with a spherical curvature sufficient that they travel back towards the thin end along paths which are parallel in Fig. 1.

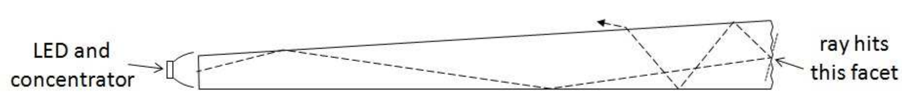


Fig. 2. Cross-section: ray angle is increased by reflection off facets at the thick end so rays emerge as they return towards the thin end.

The center cross-section of the wedge wave-guide is depicted in Fig. 2 and once rays have reflected off the thick end and are travelling back towards the thin end, we want them to reach the critical angle and emerge from the waveguide. We make this happen by embossing the thick end with facets angled so as to increase ray angle relative to the wedge surfaces.

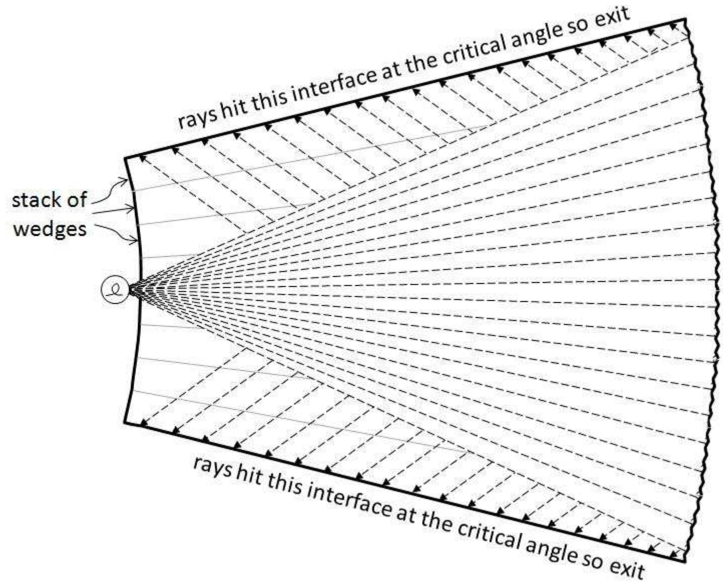


Fig. 3. Rays travel as if through a stack of wedges. The curvature of the thick end collimates the rays and the facets slew the direction of collimation so that rays illuminate the whole of the surface as they reach the critical angle.

The multiple reflections of rays traced through a waveguide quickly become a maze and it is more informative and optically equivalent to trace straight rays through a stack of replicates of the original wedge as shown in Fig. 3. The taper angle of the wedge is chosen such that both corners at the thick end are right angles so that, facets aside, the thick ends of the wedge replicates stack into a continuous curve with the same constant radius of curvature as in Fig. 1. Since the thin end is at the focal point of this curve, the length of the wedge has to be half the radius of curvature and the thin end must therefore have half the thickness of the thick end.

All rays must reach the critical angle before leaving the surface of the wedge and we wish that the emission be uniform at all points on the surface. We therefore arbitrarily pick the surface of one of the replicates in Fig. 3 and uniformly space rays which all hit this surface at the critical angle then trace them backwards to the thick end. Considering first only upward facing facets, these will focus all the backwards-traced rays to a point at the thin end of one of the wedge replicates provided that all the facets have the same angle relative locally to the plane of the thick end.

The exit surface will only be uniformly illuminated if the ray which travels horizontally towards the thick end reflects to the centre of the exit surface at a point where the wedge is three quarters of its thickness at the thick end. Making a paraxial approximation, the angle between the reflected and incident ray at the thick end is therefore three quarters of the reflected ray's angle relative to the exit surface i.e. three quarters of the difference between ninety degrees and the critical angle. It follows that the angle between the facets and the thick end must everywhere be three eighths the difference between ninety degrees and the critical angle.

We must have as many downward sloping facets as upward sloping facets at the thick end because it is as likely to be hit by rays travelling upwards as downwards. Figure 3. shows how


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rays which are not deflected so as to emerge from the upper surface of the wedge are instead deflected so as to emerge from the lower surface of the wedge and it is a simple matter to place a mirror against one surface so that the two combine. The final element is an array of prisms which bend rays so that they emerge perpendicular to the upper surface of Fig. 2.

Strict ray analysis from a point source shows illumination of the top and bottom surfaces to be finely patterned with shadows of the facets, but a finite source area and aperture diffraction off the facets cause the shadows to blur to irrelevance for most purposes.

## 3. Design

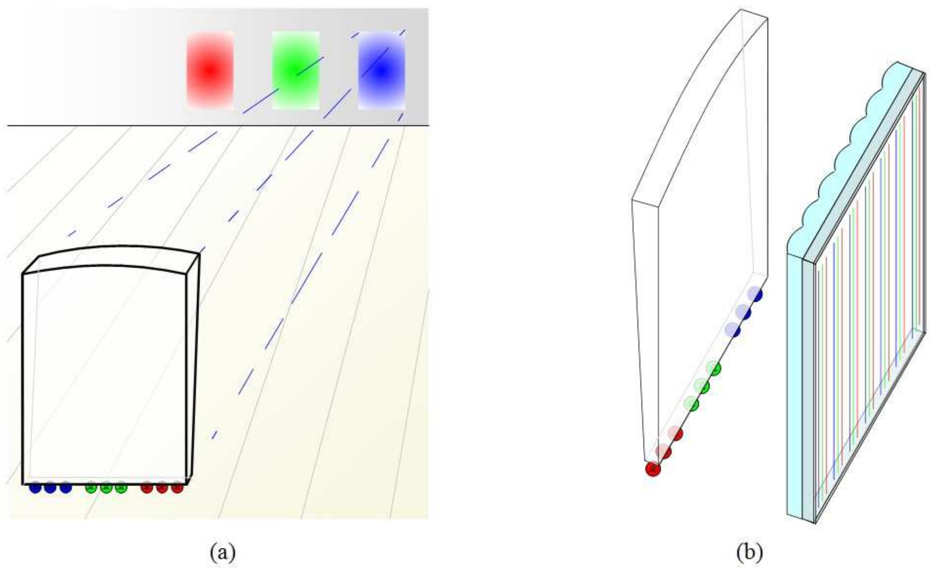

Fig. 4. The wedge collimates rays from each source in a direction determined by its position (a). Hence a cylindrical image of the sources is formed by each lenticule on the adjacent column of pixels in the liquid crystal display (b).

The color filters of a liquid crystal display are typically vertical red, green and blue stripes and each pixel of the display is a square divided into three independently switched cells which are covered by one each of these stripes. Place an array of vertical lenticules (i.e. cylindrical lenses) behind the liquid crystal panel as in Fig. 4b with one lenticule per column of pixels and if the filters are in the focal plane of the lenticules then rays from a spot source of light far behind will be concentrated through all red, all green or all blue filters, depending on its position.

We place the spot sources of light instead at the thin end of the wedge which acts as the focal plane of the wedge front surface as shown in Fig. 4a. Rays from the center of the thin end will emerge perpendicular to the light-guide surface and be concentrated through the central color filter while rays from a point to the left of center will emerge with a finite angle in azimuth so as to be concentrated through the right-hand color filter and vice versa right to left, as shown in Fig, 4b.

After passing through the focal plane, rays of light from each light emitting diode diverge so a diffuser is needed to mix the colors or else the pattern of red, green and blue light emitting diodes must be repeated along the thin end of the wedge.

## 4. Experiment

A wedge of polymethyl methacrylate with approximately the required properties was selected (linear thickness taper from 6.2 mm to 10.8 mm over a distance of 320 mm) and a curve was machined on the thick end. An extruded array of prisms was metallized, its flat side was placed against the thick end with axis of extrusion parallel to the surfaces of the wedge then

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the array was forced to conform to the curve, glued in place and the excess cropped. A transparent film embossed with a sawtooth array extruded parallel to the thin end was placed adjacent to one of the wedge surfaces, the angles of the sawtooth being such that as rays from the central light emitting diode departed the wedge, they were turned perpendicular to its surface. One red, one green and one blue light emitting diode were placed against the thin end.

The light guide was used to illuminate a Sharp K3165TP liquid crystal panel with SVGA resolution in which the color filters were vertical columns of red, green and blue with one each per pixel. The pixels measured 308 μm × 308 μm and a weak diffuser was placed against the front of the liquid crystal panel while directly behind was a lenticular array which could be aligned with one lenticule per column of the liquid crystal panel or deliberately skewed. The liquid crystal panel was set to display all white and the increase in brightness when the lenticular array was aligned versus that when skewed was found to be 2.0, 2.1 and 1.6 for red, green and blue respectively. That these are each less than 3 was found by measurement of the spectral transmission of the filters to be almost entirely due to each filter passing a fraction of the two other light emitting diodes to which it is supposedly opaque.

Bare light emitting diodes are Lambertian so in the experiment above, a significant fraction of light from the light emitting diodes was not coupled into the light-guide but instead was lost to the system. We eliminated this loss by placing a small concentrator between the light emitting diode and the waveguide. The effect of this concentrator is to project the light so that if the light emitting diode and concentrator are pointed at the lenticular array from far behind as in Fig. 4 then the lenticular array is illuminated uniformly with no overspill.

In a separate experiment, a single light emitting diode was coupled via a 9 mm concentrator into the thin end of the wedge light-guide. The brightness was measured at several points of the waveguide surface and found to be no more than 20% less than the maximum value, i.e. a uniformity of ± 10%. Power leaving the surface of the light-guide divided by power into its thin end was found to be 70% while power into the thin end divided by that leaving the light-emitting diode surface was found to be 60%. The second value is low because the protective cover on the light emitting diode prevented the concentrator being brought sufficiently close. Modelling predicts significantly less loss should light emitting diodes without the protective cover become available.

**5. Implementation**

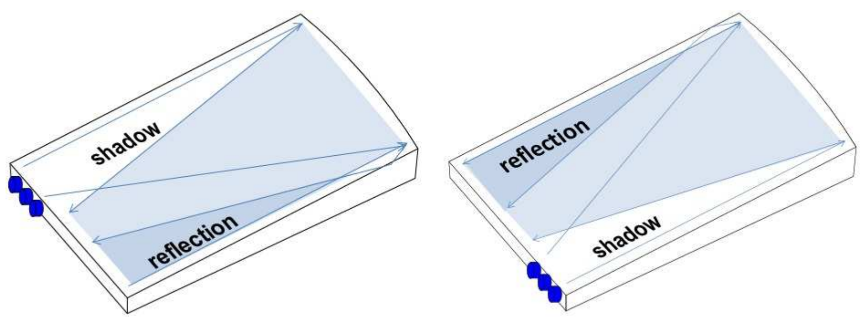


Fig. 5. Rays from LED's either side of the center will leave a shadow.

Rays either side of the center will leave a shadow as shown in Fig. 5. and while this might be hidden beneath the border of a small display such as a mobile phone, a display large enough for television will need light emitting diodes spaced all the way along the thin end if it is to be sufficiently bright yet not melt its enclosure and the triangular shadows left by light emitting diodes at either corner of the thin end would be unacceptable. However, Fig. 5 shows that if the sides of the light-guide are made reflective, there forms opposite each triangular shadow a mirror image of the triangle at double brightness so if each light emitting diode is paired with a very similar light emitting diode at the same distance from the centre but in the opposite direction, the sum of illumination from the pair is uniform.

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The red (R), green (G) and blue (B) filters of a typical liquid crystal display are ordered RGBRGB but rays set up to produce this pattern will, after reflection off the sides of the light-guide, produce its mirror image BGRBGR. We propose the halfway solution of merging two of the colors, e.g. red and blue, so as to get the symmetric pattern G(R&B)G(R&B) and leaving the red and blue color filters in place. For the simplistic target of equal powers in each color, we need RGB illumination in the ratio of 2:1:2 and the color filters will pass 3/5 of the power versus 1/3 for the conventional: an almost two-fold improvement. If makers are prepared to add a fourth column per pixel so as to eliminate entirely the need for color filters, the symmetric pattern RGBGRGBG will offer the full three-fold improvement in efficiency, as might dividing each pixel into two rows and two columns with the pattern RG on the top row, GB on the bottom row and an array of lenslets which are spherical rather than cylindrical. Lenslets might be accurately embossed from UV-curing glue directly on the LCD.

For a 16:9 liquid crystal television, the taper of the wedge must be vertical in order that we maximize space for light emitting diodes along the thin end. A spherically curved thick end will have unacceptable sag and it may be preferable that the thick end be cylindrical with the axis of curvature at the intersection of the wedge surfaces. This will of course complicate the lenticular array since focal length must linearly diminish by half from one end to the other in order to keep the pitch of illumination colors constant.

## 6. Applications

Our target here was color filters but we foresee many other applications for an imaging backlight. Firstly, we were able to concentrate light through the center of filters so as not to be absorbed by the transistor array but an even greater gain in efficiency is to limit the angle of diffusion in applications where a narrow field of view is acceptable such as portable handheld devices. Privacy is inherent here. Secondly, we might add a head–tracking camera to steer the backlight's emission in azimuth so as to get similar efficiencies even with several viewers and by alternately displaying different views to each eye, there is the potential for 3D. Thirdly, we might space the diffuser from the liquid crystal panel and make rays from the backlight diverge so as to eliminate the margin and allow panels to be tiled, or we might intermittently switch off the diffuser so as to project images to objects above the display. Fourthly, the absence of scatter should make the guide an efficient front-light and color stripes projected on displays made monochrome to optimise use in daylight might enable color video at night.

We believe that by deliberately introducing scattering sites into backlights, many designers lose the gains to be made from the low étendue of light emitting diodes. We have tried to show the advantages to be gained by instead using shape to distribute light across the system as if the liquid crystal panel were part of a system of projection. Finally, we note that although it necessarily has a rear focal plane shaped like a slit, the light guide reported in this article has many of the features of a lens without the commensurate bulk so we hope for other applications.

## 7. Conclusions

We have demonstrated a flat panel backlight which emits uniform collimated illumination from the entire area of one surface when a single light emitting diode is placed at one end. A uniformity of ± 10% and light guide efficiency of 70% have been demonstrated but we expect improvement to be simple and significant. A red, green and blue light emitting diode at one end have been imaged via a lenticular array onto the color cells within a liquid crystal panel so as to halve power consumption. We anticipate not only the elimination of color filters and expensively matched light emitting diodes, but further significant reductions in power consumption and wider application stemming from the ability to project through the backlight.

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