P.64: Modeling Color Separating Backlight with Internal Mirrors

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Abstract
Ray tracing models the behavior of a LCD color separating backlight to optimize its efficiency by establishing the optimum dimensions and position for a micro-mirror array within the lightguide. It also includes a total internal reflection lightguide, arrays of three color LED light sources, cylindrical micro-lenses and discrete color separating diffraction gratings.

1. Introduction
Transmissive Liquid Crystal Displays (LCDS) have found wide application in desktop and laptop computers, in palmtop personal organizers and in aircraft displays, for example [1] because compared to CRT monitors they offer smaller footprints, lower weight, thinner size, higher luminance, lower power, are less susceptibility to magnetic fields, and give a flicker-free image. However, only a few percent of the light generated by the backlight emerges from the display screen [2]. At least two thirds of the light is absorbed by the color filters and at least a future half by the polarizers. The backlight illumination is usually continuous over the whole display but only light falling onto the pixel apertures passes through the display, causing loss by this fill factor or aperture ratio. The performance of the liquid crystal display can be improved in several respects: improved conversion efficiency of light generated by the backlight to modulated light emitted from the front of the display to the viewer, ideally no polarizers or color filters, lower electrical power consumption, small size efficient light source, e.g. LED, higher contrast ratio, good uniformity of illumination, low cost and ease of fabrication of the backlight and wide viewing angle. In each application the priority of each of these attributes varies. This paper reports modeling of a novel backlight design which uses red, green and blue LEDs, a single thin lightguide, an array of separate gratings on the surface of the light guide, an array of micro-mirrors in a layer inside the light guide, and an array of double convex cylindrical lenses directly below each set of three LCD pixels. The lightguide modeling is described and used to optimize the contrast and to improve the efficiency by separating the three colors and collimating the three narrow beams so that they pass through the centre of each pixel so avoiding the need to use the highly lossy and costly color filters. The main aim of this paper is to correctly model the full backlight structure so that the optimum size, width and position of the micro-mirrors can be established for this backlight structure.

2. Color separating backlight structure
Figure 1 shows one of the micro-optical subsystems in the backlight used to illuminate a set of three red, green and blue pixels. This system is replicated many times to form an array along the length of the light guide. Red, green and blue LED chips glued to one edge at one end of the lightguide provide the optical sources for the side illumination. The light guide is a thin, transparent uniform thickness sheet made of glass or replicated into polymer and operates by total internal reflection. The light guide has on its upper surface a periodic array of discrete gratings each of limited extent which act as grating coupler "windows" through which light periodically exits from the lightguide and also angularly separates the colors by diffraction. Two arrays of convex cylindrical microlenses are placed directly above each grating. These are separated vertically to form a "thick" microlens combination. The microlenses convert the angular separation of the three color beams into a spatial separation and collimate the beams so that they provide illumination normal to the LCD and separate them sufficiently and narrow the beams so that they pass thorough the centre of each corresponding LCD pixel. An array of thin metallic mirrors in a layer are embedded or placed within the light guide. The mirrors are reflective on both their upper and lower surfaces.

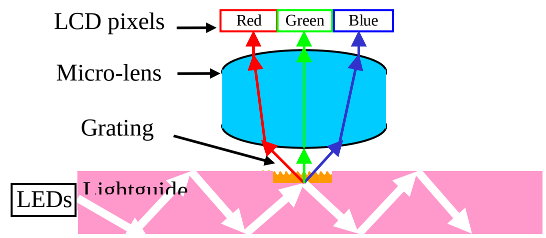


Figure 1 Backlight illumination system with cylindrical micro-lens array (1 pixel)

2.1 Light source
The benefits of using LEDs as a light source for edge-lit backlights have been previously expounded [3, 4, 5]. This illumination system places three colors of LEDs, an array of red, green and blue, along the edge of the highly multimode light guide. The light is injected into the light guide, which mixes the three colors to give an effective white which is distributed along the length of the lightguide. Our model uses chip LEDs without integral lenses, mounted at the entrance to the guide. The chip LEDs act as very small, almost point, sources on the entrance surface of the lightguide. The Lambertian emission profile results in rays emerging from the chip LED at many different angles within a hemisphere so only a very short mixing section is needed to realize the effectively white light [6].

2.2 Lightguide
The dimensions of the lightguide used in the model were chosen to lie beneath a 20 × 75 pixel LCD. This is sufficient to understand its behavior as the optical micro-elements repeat themselves along the guide. It also allows the calculations to be performed in a reasonable length of time. The light guide dimensions are 6.62 × 25 mm with a thickness of 0.99 mm. It is

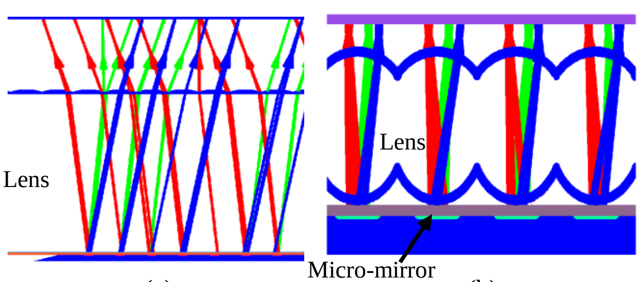
formed as a total internal reflection light guide without cladding, from a transparent polymer with a refractive index of 1.50 giving a critical angle by the formula [7], $\sin\theta_c = n_t / n_i = 0.67$, ($\theta_c$ = 41.8°) where n_i is the refractive index of the core and n_t is the refractive index of the cladding. The transmitted angle is $\sin\theta_t = \sin(90^o - \theta_c)$, ($\theta_t$ = 48.2°). $\theta_t > \theta_c$, therefore in the lightguide the angular distribution is bounded within 41.8°. According to Snell's Law, all rays incident on the entrance of lightguide at angles less than 90° will strike the interior wall at angles greater than θ_c and will pass through along the lightguide. We also assume that the LED is either just inside of the guide or glued with an optical quality index matching cement to the surface of the light guide edge so that we can ignore reflections of rays from the lightguide end surface.

2.3 Gratings

When light entering the multimode lightguide emerges at the periodic grating "windows", the three wavelengths are separated from one another by the diffraction grating. A micro-lens array is placed just above the grating "windows" to take the light from the grating surface and to make it collimated normal to the display and to aim it at the centre of each pixel. So the red, green and blue beams are parallel to each other when they arrive at their corresponding sub-pixels, and normal to the display to maximize contrast.

2.4 Modeling Results

Figure 2, showing the behavior of the rays, was created using a non-sequential ray tracing package ASAP 7.1.8 [8]. The backlight design was optimized for color separation by: positioning the micro-lens array between the light guide gratings and the LCD panel, calculating the curvature of the double convex lens, modifying the lens thickness and modeling materials with different refractive indices.



(a) (b)

Figure 2 (a) A single surface convex lens; (b) A doubly convex "thick" cylindrical microlens or two arrays of cylindrical micro-lenses with micro-mirror array in the lightguide.

The grating surface has a very fine pitch with a period of the wavelength of green light, about 0.5 µm. Apart from the zero order beam which reflects most of the light back into the lightguide at the same angle, the first order transmitted beams are the ones that pass through the micro-lens arrays but the first order reflected beams are a mirror image of them and travel downwards at a steep angle into the guide and then directly out of the lower surface of the guide as they are below the critical angle for the guide. This loss can be avoided by embedding or placing within the guide an array of micro-mirrors, parallel to and beneath each grating to reflect these beams out of the grating "window" with the first order transmitted beams. We do not believe that these internal embedded micro-mirrors have been used before except on the lower surface of the light guide. The micro-mirrors are shown, to scale, in figure 2 but they are only 10 µm below the lightguide surface gratings so they only appear as a thin dashed line.

3. Internal Mirrors

3.1 Mirror Depth

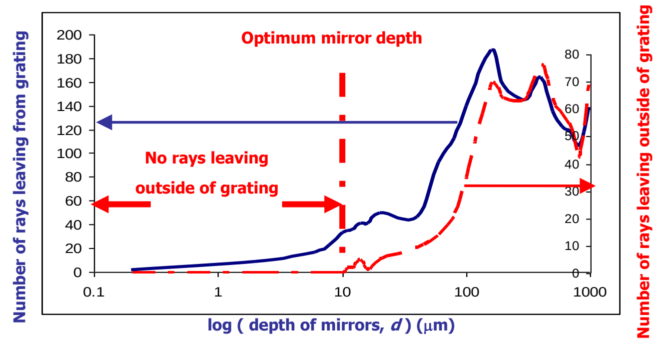


Figure 3 Number of rays arrives at LCD as a function of micro-mirror depth

In order to find the optimum position of the micro-mirrors, we fixed the width of the mirrors and varied the depth. As we moved the mirrors from the upper surface to the lower surface of the light guide, the number of rays leaving the guide at the grating increased. However, when the micro-mirrors were placed deeper than 10 µm some light exited the lightguide at the top surface but outside the region. This makes the proper design of the multiple micro-lens subsystem difficult as the top surface effective source becomes extended. So the best position was found from figure 3 to be 10 µm which is a conveniently small figure to envisage realistic fabrication procedures for this internal or embedded micro-mirror array layer. In this paper we do not investigate the optimum angle of the micro-mirrors but keep them parallel to the top surface of the lightguide since this arrangement makes them easy to fabricate using photolithographic techniques.

3.2 Mirror Width

If the width is set too small, figure 4, some first order reflected light passes through the gaps between the micro-mirrors and exits the lower surface of the guide.

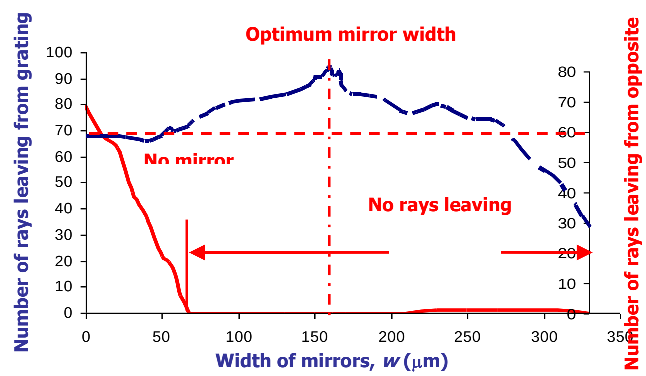


Figure 4 Number of rays arrives at LCD as a function of micro-mirror width

If we choose a sufficiently wide mirror, 69 µm, this light will all be blocked, figure 4. However, it the mirror is too wide it will block the rays from the light guide reaching the grating and so reduce the rays reaching the LCD cutting down the brightness and efficiency. We fixed the mirror depth at the optimum of 10 µm below the upper surface of the light guide and varied the width from the minimum of 0 µm to the maximum of 331 µm. Figure 4 shows that the optimum mirror width is w = 160 µm.

3.3 Depth/Width coupling:

In fact the micro-mirror depth and width are coupled in their effects and so cannot be considered correctly, each in isolation of the other. So we have calculated and plotted a contour map (figure 5) showing their relationship. The optimum occurs at the marked point in figure 5 at d = 10 µm, w = 160 µm. Figure 4 shows that the light at the LCD panel at this point increases by 38.2%.

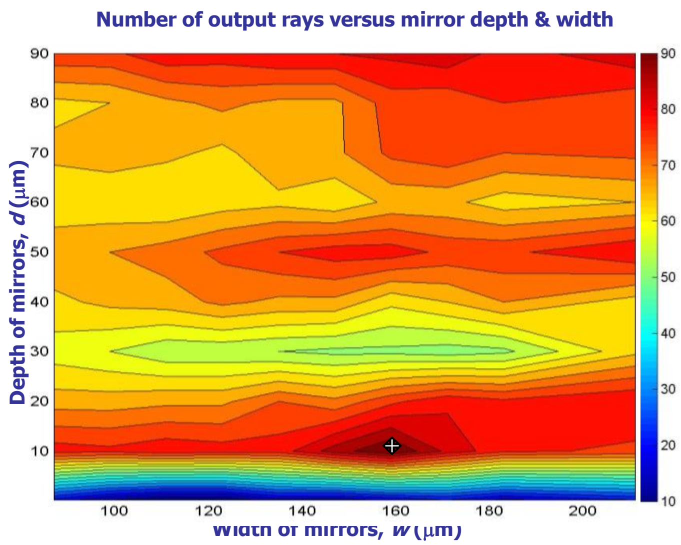


Figure 5 Contour plot of the number of output rays as a function of both depth and width of micro-mirrors.

4. Summary

Our research uses a uniform thickness guide which simplifies the fabrication procedure as it is convenient for use width photolithographic techniques. Periodic, limited length, discrete gratings are used instead of a continuous grating surface. This allows us to control the size of the exit aperture from the light guide, and, thence, the diffraction pattern from it. It also allows us to control the strength of each grating window individually by either varying the modulation depth of the grating or the length of each grating, thereby, obtaining better uniformity. We use two cylindrical microlens arrays which give more design variables to enable optimization of collimation normal to the display at the centre of each pixel of red, green and blue respectively. The horizontal micro-mirror array inside the lightguide improves the overall luminous efficiency. We use, almost point light source, chip LEDs instead of fluorescent tubes due to low power consumption, long lifetimes and good efficiency for the full system from electrical input to modulated light emerging from the display. Our paper describes modeling to optimize the micro-lens array design and to study the inter-dependence between the depth and the width of the micro-mirrors which were not covered in our earlier paper on micro-mirrors [9].

5. Acknowledgements

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