A novel diffractive backlight concept for mobile displays

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Abstract — Power-efficiency demands on mobile communications device displays have become severe with the emergence of full-video-capable cellular phones and mobile telephony services such as third-generation (3G) networks. The display is the main culprit for power consumption in the mobile-phone user interface and the backlight unit (BLU) of commonly used active-matrix liquid-crystal displays (AMLCDs) is the main power drain in the display. One way of reducing the power dissipation of a mobile liquid-crystal display is to efficiently distribute and outcouple the light available in the backlight unit to direct the primary wavelength bands in a spectrum-specific fashion through the respective color subpixels. This paper describes a diffractive-optics approach for a novel backlight unit to realize this goal. A model grating structure was fabricated and the distribution of outcoupled light was studied. The results verify that the new BLU concept based on an array of spectrum-specific gratings is feasible.

Keywords — *Active-matrix liquid-crystal display (AMLCD), backlight unit (BLU), diffractive optics.*

1 Introduction

Recent developments in mobile communications terminals and networks have led to increased demands on the power efficiency of handheld communications devices such as mobile phones. With the rapid adoption of third-generation (3G) networks and mobile digital television broadcasts, the mobile terminal is becoming a major multimedia appliance for everyday use. The mobile-phone user interface (U1) has been shown to dissipate roughly one third of the electrical power of a mobile phone.[1] Displays especially are a drain on the current shared by other functions of the mobile terminal, and developments in the display power efficiency are sought after.[2]

The backlight is the dominating component in the display-module power consumption, particularly in the case of transmissive liquid-crystal displays (LCDs) for multimedia applications which require higher color saturation and perceived brightness. Current backlight designs are based on creating a uniform distribution of white light throughout the display pixel matrix, which in the majority of cases is an active-matrix liquid-crystal display (AMLCD). Although this design results in a relatively compact and simple structure with moderate needs for lateral alignment of the optical films in the display, a large fraction of light generated in the light-emitting diodes (LEDs) of the backlight module is wasted in the absorption of unwanted spectral content in color-filter arrays, as well as in the opaque areas of the AMLCD matrix thin-film transistor (TFT) and reflector arrays. One way to improve the light throughput is to use field-sequential color (FSC), where instead of separating the color primaries spatially by arranging them in subpixels, color is separated in a temporal fashion and modulated by a monochrome matrix.[3] The problem in this approach is the duty cycle, reducing the effective light throughput in time to less than one-third of the available frame sequence and the need for faster and thus more expensive liquid-crystal materials, TFTs, and driver components.[3]

Directing the emitted light only to the active pixel areas where its spectral content matches the respective primaries of the color-filter array would help in curtailing the power drain of the display module and thus enabling an increased overall power efficiency in a mobile-phone user interface.

This paper presents a new diffractive optics concept for spatially modulated display backlights, such as LCDs, with color-selective extraction of light matching the respective primaries of the color-filter pixel matrix. An experimental study was performed with a striped model grating array representing a 1 cm by 1 cm area of a prospective 2.8-in. QVGA (320 × 240 pixels) display in order to verify the concept.

2 State of the art of backlight units and the diffractive backlight concept

2.1 State of the art of backlight units

Early mobile phone backlight units (BLUs) were simply roughened pieces of transparent polymer, molded to fit the frame of the display module. In the back of the BLU there was a reflector film. Hotspots from LEDs could be a problem, and they were taken care of by darkening the reflector area near the illuminating LEDs, if at all.[4] Later on, with

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increasing legibility demands, glare from the display was reduced by directing the specular reflections of the ambient light out of the viewing direction.[5] While these approaches were adequate for monochrome displays, it became apparent with the emergence of color LCDs in mobile phones that a high contrast and good color gamut with an adequate viewing angle was to be required of mobile displays.[6] The focus of development was shifted to adding collimating films in mobile and laptop LCDs to control the propagation of light through the pixel array.[7] Concurrently, white (or "pseudo-white") LEDs appeared as light sources in color LCDs, since the previously used green LEDs obviously could not provide the desired spectral characteristics for the new full-color UIs.[2]

Most notably, the BLU light-guide structure evolved, from the molded polymer component with a roughened surface to precisely engineered plates with efficient incoupling lens areas[8,9] and statistically distributed scattering centers made by screen printing on the back of the BLU light guide. The main improvement, however, came about when the scattering centers were replaced by microreflectors.[10–13] These structures can, in principle, be very efficient directing most of the light emitted by the LEDs into the AMLCD color-filter array with better than 80% uniformity.[13] Thus, the state-of-the-art mobile BLU today is a stack of optical films, with a reflector structure as the bottom-most surface. The emitted light from LEDs is coupled into the light guide, and the microreflector structure directs the light toward the display itself. Two brightness-enhancing films (BEFs) are typically used, perpendicularly to each other, to collimate the light through the LCD and to provide a degree of polarization recycling. The optics stack is completed by adding the LCD with polarizers on both sides to modulate the light emerging from the BLU by the AMLCD matrix, which typically consists of an array of red, green, and blue subpixels. The main drawback of this structure is that the light emitted by the white or pseudo-white LEDs is not separated to the primary-color bands of the subpixels in the AMLCD matrix. Therefore, in the ideal case, only one-third of the light in a typical LCD can pass through each pixel. Furthermore, since the active-matrix TFT array has an active aperture that is limited by the transistor structure and in the case of transflective LCDs, also by the reflector area, the throughput of light is further reduced to roughly two-thirds of the available illumination through each subpixel. The LCD polarizer further reduces the throughput to one-half or less of the light emerging from the BLU. Thus, the efficiency of the whole array, not accounting for the transmissivity losses in the LCD color filter and the material losses in the optics stack of the display, is on the order of 10%.

To increase the efficiency and to decrease the thickness, polarizing backlights have been proposed.[14–19] Also, several of the functions traditionally incorporated in single and separate films have been combined as hybrid films.[20] This development has led to thin mobile-display structures, in conjunction with engineering efforts to reduce the overall thickness of mobile displays and mobile LCD modules less than 1 mm thick have been reported.[21]

Diffractive components have been previously proposed for color-imaging applications.[22] These early diffractive-grating-based systems employed relative coarse groove periods on the order of several micrometers, and spectral separation was only possible with an adequate back distance from the imaged scene.[22] In the area of display technology, holographic films have been developed for mobile LCD panels to be employed in various functions.[8,9,23–25] These films use surface-relief holograms to diffract a desired polarization state of light into the LCD panel[8,9] or to diffuse the emitted light in a precise way to control the viewing angle of the display.[23–25] These applications of holographic films in mobile LCD development are examples of using diffraction in BLU design, and in the polarizing holographic BLU, the hologram is essentially a submicrometer period diffraction grating.[8,9] Diffractive backlights have also been proposed with a pixelated single-period grating pattern.[26] Ray-tracing models showed that the backlight using the pixelated single-period gratings requires both microlenses to direct the light onto the respective pixels and thin micromirrors inside the grating structure to reflect the negative diffraction orders back into the desired direction.[26] The uniform-sheet approach in diffractive backlights also would require a lenticular lens sheet to direct the spectrally spread emission from the light sources to enter the desired subpixels in the TFT array, as the spectral divergence is large.[8,9]

2.2 Diffractive backlight concept

Previous studies indicate that high-efficiency gratings can be manufactured on polymers, in a replicable fashion, for example, for personal-display exit-pupil expanders (EPEs).[27–30] The gratings are made by optical or electron-beam lithography on fused silica masters and then replicated by molding. Thermal or ultra-violet (UV) curing and sometimes embossing can be used to replicate these gratings multiple times.[30] It is possible to achieve high efficiency, experimentally verified up to 80%, in outcoupling of light by these gratings by controlling the light distribution into selected diffraction orders, and the gratings can be made wavelength-selective so that only determined color bands of light are coupled out of the grating structure.[30] The EPE studies also indicate that it is possible to manufacture efficient fan-out gratings for the distribution of light uniformly along the EPE plate. It has been shown that the EPE gratings can be replicated repeatedly, up to hundreds of times from a single master, by UV embossing.[30]

Figure 1 shows a schematic outline of the new pixelated diffractive backlight concept. Incoming light is fanned out by a grating that is selective for each primary color, and respective red, green, and blue LEDs are used for the color primaries. The light is then distributed throughout the active area of the display by total internal reflection

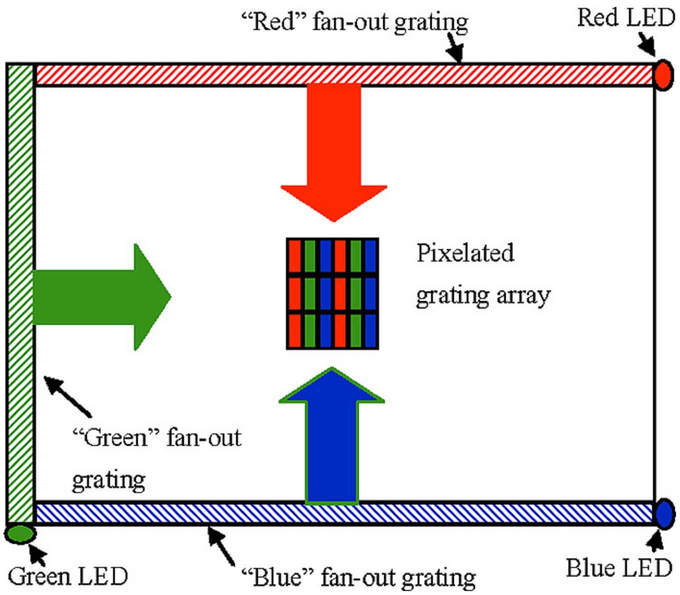

FIGURE 1 — Pixelated backlight concept (not to scale).

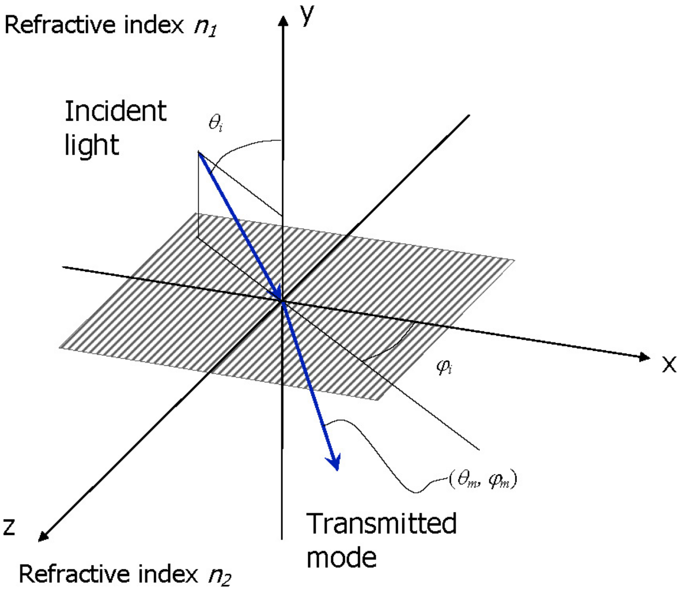

FIGURE 2 — The coordinate system used in grating design.

(TIR). In the active area, an array of gratings couples out the light into the active aperture of the display pixel matrix. The separation of color primaries at the pixel level is achieved by color-specific gratings, and by orienting the green-primary light propagation inside the TIR light guide perpendicularly to the red and blue primaries.

3 Model grating design and experiment

3.1 Model grating design

The conical grating equations [Eq. (1)][31] for the light coming from the material 1 to material 2, represented by refractive indices n_1 and n_2, respectively, through a grating interphase are

$$\begin{aligned} n_2 \sin\theta_m \sin\varphi_m &= n_1 \sin\theta_i \sin\varphi_i, \\ n_2 \sin\theta_m \cos\theta_m &= n_1 \sin\theta_i \cos\varphi_i + m\lambda/d, \end{aligned} \tag{1}$$

where d is the period of the grooves in the grating, θ_i is the angle of incidence, θ_m is the diffracted angle with respect to the surface normal of the plate, φ_i is the incident, and φ_m is the diffracted azimuthal angle of the light, m is the diffracted order, and λ is the wavelength of light incident on the grating (see Fig. 2). Light that is trapped inside a light guide due to total internal reflection (TIR) has an angular intensity distribution that depends on the light source and on how the light is coupled into the light guide. Because the diffraction efficiency of surface-relief gratings typically depends strongly on the incidence angles, a unidirectional light field traveling close to the TIR limit would provide the optimum case for controlling the properties of the outcoupled light. In practice, the incoupling angles in the range of θ_i = 45–65° and φ_i = –10° to +10° are sufficient for most cases. The diffraction angles for the outcoupled light of the mode m in the case of $n_1 = n$ and $n_2 = 1$ (air) can be written as

$$\begin{aligned} \tan\varphi_m &= \frac{\sin\theta_i \sin\varphi_i}{\sin\theta_i \cos\varphi_i + m\lambda/nd}, \\ \sin\theta_m &= \sqrt{n^2 \sin^2\theta_i \sin^2\varphi_i + (n \sin\theta_i \cos\varphi_i + m\lambda/d)^2}. \end{aligned} \tag{2}$$

Equation (2) shows that the diffraction angles of the maxima of the diffracted orders of light follow the incident angle of the corresponding light and are strongly dependent on the wavelength. The gratings should be constructed so that they are selective for wavelengths and so that the distribution of outcoupled light can be controlled spatially. If the grating period is sufficiently small, only the first-order diffractions ($m = \pm 1$) are present at small azimuthal angles ($\varphi_i \sim 0°$). Moreover, it can be seen from Eq. (2) that only the zeroth-order diffraction exists at large azimuthal angles. This means that the outcoupling of two different wavelength bands can be decoupled by using gratings with perpendicular groove directions. This enables color-selective outcoupling for two primaries, but leaves the third one mixed with either one of the first two. Because of the large spectral separation between red and blue wavelength bands, it appears attractive to decouple the outcoupling of green from red and blue with the aid of the perpendicular gratings. For blue–red separation, we need gratings that are either strongly wavelength or incidence-angle dependent, *e.g.*, the illumination direction for the red and blue primaries can be from opposite directions.

The condition for light outcoupling along the normal direction can be obtained from Eq. (2) by setting $\varphi_i = 0$, $\theta_m = 0$, and $m = 1$

$$d = \lambda / n \sin\theta_i. \tag{3}$$

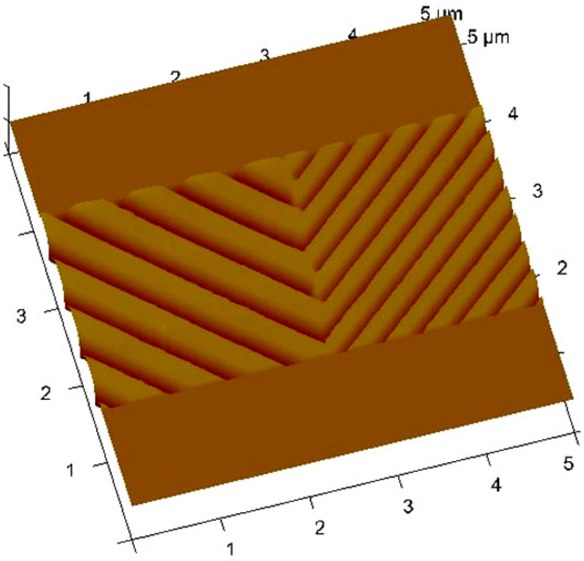

FIGURE 3 — Atomic force microscope (AFM) image of the grating fused-silica master, showing sections of the gratings used for green and red/blue primaries.

Equation (3) shows that subwavelength outcoupling gratings are needed for TIR light guides. Also, it can be seen that only one wavelength at a given incidence angle is outcoupled along the surface normal. Because we only have two different optimized grating periods for green and blue, the third wavelength band of red light will not emerge out from the light guide perpendicularly. The outcoupling angle for the red light is approximately

$$\sin\theta_R = (1 - \lambda_R/\lambda_B) n \sin\theta_i, \tag{4}$$

where λ_R and λ_B refer to red and blue wavelengths. The grating period for blue would be about 390 nm if the blue light is to be emitted perpendicularly, but in this case we can intentionally make the period smaller because then the intensity of red diffracted light becomes smaller. The blue emission deviates now from the normal at about 20° and red is at very high angles, more than 50°. The red emission from this grating is also weak. In optimal grating arrays, the red light needs its own outcoupling gratings, where the emphasis in design would be in weak blue outcoupling. This is one possible way for spatial separation of blue and red wavelengths. The incoming angle θ_i should be selected so that the whole wavelength band of the LED emission will be confined inside the plate due to TIR. The angular distribution of the LED emission typically will be the dominating characteristic in the respective angular distribution of the output coupling, due to the relatively narrow wavelength bands of LED emission.

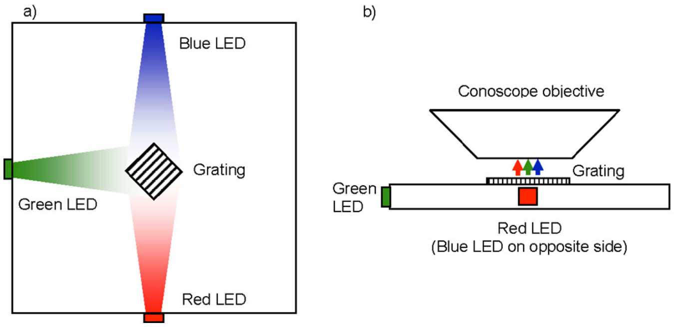

FIGURE 4 — Experimental setup (not to scale): (a) schematic view from above, (b) cross-sectional view.

TABLE 1 — Grating parameters and expected efficiency of the gratings.

Primary	Width (µm)	Depth (nm)	Grating period (nm)	Calculated efficiency of transmitted mode at $\theta_i = 55°$, $\varphi_i = 0°$	
				TE	TM
Red and blue	118	220	450	0.150 0.182	0.040 0.061
Green	59	220	300	0.204	0.044

3.2 Model grating experiment

A small binary grating structure of 1 × 1-cm square, with 50% filling ratio, was fabricated on a plate of 1-mm-thick polymethyl methacrylate (PMMA) in a mold using UV-curable material SK9 at NanoComp Oy in Joensuu, Finland. The grating parameters as well as the theoretical outcoupled efficiencies for the gratings are shown in Table 1. The result is a stripe array with one grating used for both red and blue and one for green (Fig. 3). The red and blue light are directed to the grating from opposite corners of the grating area, and green perpendicularly to these. The grating directions are 45° and 135° with respect to the stripe orientation.

Osram LEDs were used as light sources.[32,33] The LED parameters are shown in Table 2. Small, 0.6-mm-thick LEDs were used for efficient coupling of light into the sheet of PMMA.

Figure 4 shows the experimental setup. The LEDs were mounted on the sides of the grating plate, and ordinary butt-coupling was used to launch light into the plate of PMMA which then acted as a TIR light guide. The divergence of the LEDs was utilized to partially fan out the light across the grating area. The grating plate was placed in front of an Eldim EZLite 120 R conoscope and polar plots of light intensity were obtained for all individual colors as well as for the combined red, green, and blue LEDs all on.

TABLE 2 — LED parameters (Refs. 32 and 33).

Primary	Dominant wavelength (nm)	FWHM* (nm)	Luminous intensity at 20 mA (mcd)	Luminous efficiency (lm/W) (typical)
Red	625	19	180…900	43
Green	528	33	560…1800	36
Blue	460	25	90…280	11

*FWHM: Full width at half maximum.

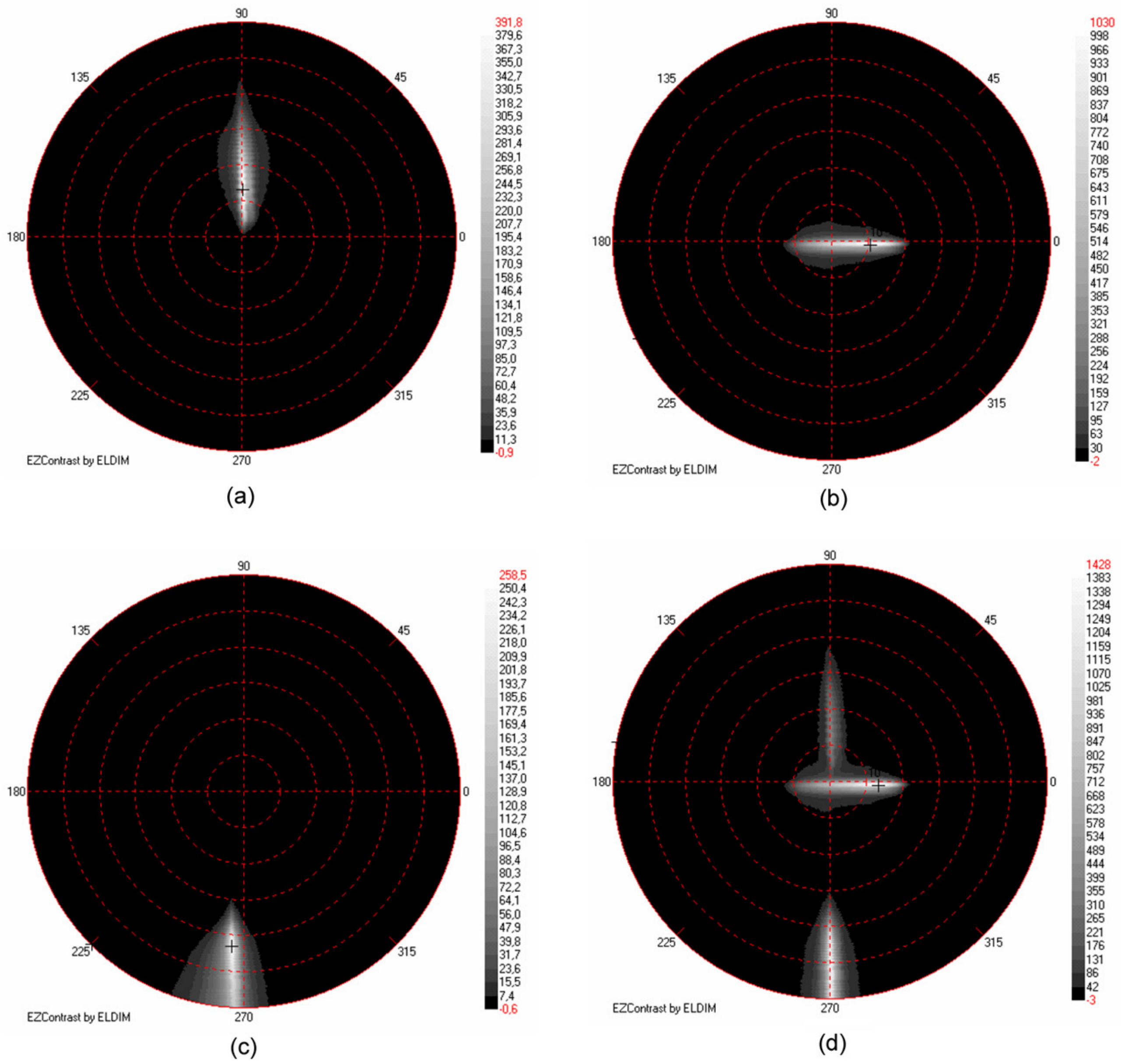

FIGURE 5 — Polar coordinate plots: (a) blue, (b) green, (c) red, and (d) all combined.

4 Results

Figure 5 shows the polar plots obtained with the Eldim EZContrast conoscope. It was found that the joint grating for red and blue coupled out blue light, significantly better than the red, to the viewing direction. The red outcoupling was preferential in an oblique angle. The green outcoupling was also observed in an angular range directed effectively toward the viewer. The division of the outcoupling was clearly visible as can be seen from Fig. 6. The green light coupled out of the narrow grating stripes, and the blue and red coupled out of the double-width grating stripes. The red outcoupling could not be photographed because the light coupled out of the aperture of the microscope. Because we did not have a fan-out grating in this experiment, it is clear that the uniformity of illumination was not very good. There was a visible streak of light in the middle of the structure for the blue and green primaries showing efficient outcoupling of light. The red emission streak was observed only by view-

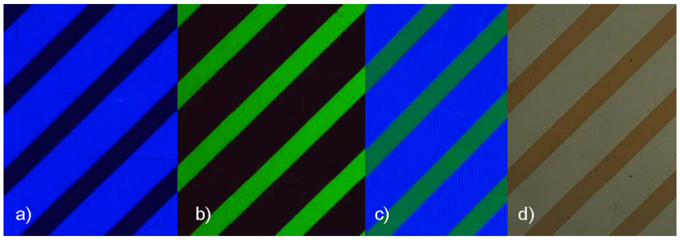

FIGURE 6 — Microscope image of the outcoupled light from the grating array: (a) blue LED on, (b) green LED on, (c) blue and green LEDs on, and (d) optical microscope image.

TABLE 3 — Angles about the zenith of the outcoupling maxima in the model grating experiment.

Primary	Angle of maximum outcoupling (°)
Blue	15.0
Green	10.5
Red	58.0

ing the grating array obliquely from the LED side of the grating plate.

Table 3 summarizes the results of the measurement with the conoscope. Grating efficiencies were not characterized, but the luminance values in the conoscope results (over 1400 cd/m^2, all LEDs on) show that the emission from the gratings would be adequate for a mobile LCD BLU at least for the blue and green primaries, if properly arranged uniform lighting were to be implemented in a real BLU design.

Compared to the outcoupling characteristics expected from theory, it is evident that the angular range of outcoupling falls within the theoretical outcoupling range. The intensity distribution of outcoupled light shows that the conical grating theory explains the emission adequately. The outcoupling was very narrow in the azimuthal direction for the outcoupled bands of light for each primary color. The direction of the outcoupling for the red was near the maximum measurable angle of the conoscope (60°), and therefore the actual value is only estimated to be near that maximum angle. For an accurate analysis of the outcoupled distribution, comparing it to theory would require more extensive modeling. For the purpose of verifying the diffractive BLU concept, these experiments are adequate.

5 Conclusions

In principle, the results show that a diffractive BLU concept based on a pixelated structure of gratings with grating parameters selected for the respective primary colors of the backlight light sources is possible.

It is clear from the results that the blue and red grating used as a joint outcoupling structure is not effective for both bands of light. This was expected also from theory. Therefore, a dedicated grating for each primary color is needed. The original principle of separation of green and blue by having the green grating perpendicular to the red and blue grating was working, and the rejection of unwanted radiation from both gratings was observed.

With a fan-out grating, the directive effect of the light emission could be spread out throughout the structure, most likely giving good outcoupling characteristics and a good uniformity across the whole backlight module. A diffuser would be needed on top of the display stack to control the eventual viewing-angle characteristics of the display. Also, in an actual BLU based on grating arrays, a degree of modulation based on the diffraction efficiency or the proportional area of the grating with respect to the intended subpixel needs to be designed in the BLU to improve the uniformity of the illumination.

The concept presented in this study could effectively reduce the display backlight power dissipation significantly to enable slimmer, smaller and smarter mobile phones with brighter video-capable displays. Ideally, compared to the state of the art, by directing the respective primary spectral bands of light from the red, green, and blue LEDs through their respective color subpixels, the efficiency of a display system could be increased from roughly 10% of today's to nearly 100%. Furthermore, by using dedicated primary color lights sources for red, green, and blue illumination, controlling the display color space and optimizing the power usage of the display would be easy to realize by software means. The resulting structure of the BLU would in principle also become simpler by using diffractive light guides because there is no need for collimating films between the BLU light guide and the LCD. However, there remains the need to register the BLU and LCD subpixels on top of each other, which adds an alignment step in manufacturing. In addition, for best efficiency and for best rejection of cross-talk, slanted gratings[30] would be required for all respective primary colors in the BLU array, making the master-grating-array manufacturing a complicated process.

Expanding the scope of pixelated diffractive BLUs beyond mobile-phone use would impose demands on alignment accuracy, and thermal-expansion issues in large-area systems such as in LCD-TV displays would especially require special attention.

We aim to further study larger structures based on more complicated and truly pixelated grating arrays. Also, a verification of a fan-out grating is needed to determine the feasibility of the concept to be integrable in a real display. Studies with actual displays in conjunction with these backlight structures are in the planning phase.

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