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Large-gamut color and spectral display using sub-wavelength gratings

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Abstract

As content creation, editing, approval, prototyping, manufacturing and consumption become ever more distributed, the ability to display a broad variety of colors becomes increasingly more important. Displays that use RGB filters or even backlights cannot span all spectra or even just colors that occur in nature. To improve the accuracy of spectral and color reproduction, there have been attempts to include additional color primaries in displays. Existing solutions, however, impact cost, scalability, or spatial resolution and are predominantly applicable to projections system. We propose an approach based on combining diffraction gratings extractors (Fattal et al., 2013) and the HANS imaging pipeline (Morovič et al., 2011) initially developed for printing. This combination offers access to a very large color and spectral gamut with the same backlights as commercially used today.

Introduction

Displays are used ubiquitously in the process of creating and consuming digital content. Additionally, they are also widely used as windows to remote events and as means of previewing objects before their production. The range of colors and spectra that they are capable of rendering is very important for all these applications and for a variety of reasons. In manufacturing, a display capable of showing all the colors that a given object exhibits under a variety of lighting conditions has the potential to replace or significantly reduce the production of prototypes. In entertainment, a display capable of more faithfully rendering the variety of colors present in nature – especially under mixed illumination conditions – can result in experiences that are more vivid, life-like, intense, and convincing. When used as a component of an object that consists both of reflective parts (e.g., plastic, rubber, metal, etc.) and of a display or multiple displays, e.g., the e-ink smart-shoes introduced in 2015 (cnet, 2015), a display capable of outputting light with specific spectral characteristics would allow for a level of overall consistency of appearance that is impossible today.

Current displays use a white backlight and absorptive filters, or colored backlights, usually of red, green and blue appearance. This approach achieves a limited gamut because, to achieve sufficient luminance, the filters are relatively broadband and therefore incapable of approaching the locus of spectrally pure color stimuli. A display with an enhanced gamut requires multiple narrowband backlight sources. However, displays using more than 3 or 4 primaries at a time have prohibitive cost and size.

Conventional approaches to achieve large gamut displays require the use of multiple narrow band light sources (e.g., lasers (Brazas and Kowarz, 2004), quantum dots (Kwak *et al.*, 2012)) or notch filters, either absorptive or interference), which are generally costly and have limited resolution imposed by the manufacturing and assembly of the filters.

Nanostructure gratings for displays

We propose a design based on nanostructures that can increase the number of color primaries, achieving a large color and spectral gamut and maintaining at the same time small pixel size and therefore high resolution. In our solution a glass substrate is illuminated from the side with a white LED or RGB LEDs. The light traveling inside the substrate interacts with an array of diffraction gratings patterned on the surface. Each grating (subpixel) is designed such that light at a specific wavelength is emitted outside of the substrate in the direction orthogonal to the display, where the spectral and color selection in each subpixel is related to the period of the grating (Fattal *et al.*, 2013). The designing of the geometry of each grating then allows for any combination of colors (primaries) to be selected. A liquid crystal display (LCD) is placed on top of the substrate so that each cell is overlaid with a subpixel, creating a shutter plane to enable dynamic primary selection. A viewer standing in front of the screen then receives only light from the primaries that are open while the rest of the illumination is scattered to the side (Fig. 1). Note that a blocking mask and a diffuser can be used to extend the field of view here.

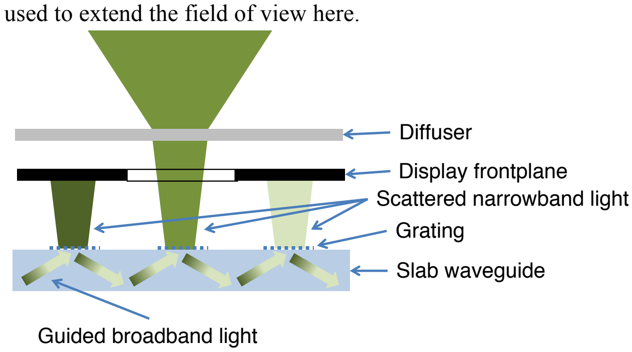

Fig. 1: Basic principle of display operation.

The advantage of this approach is given by the design versatility and compactness: an arbitrary number of subpixels can be used to create the desired primaries; moreover the gratings can be easily tiled to create a pixel. The grating subpixel matrix can be patterned using large-scale lithographic techniques (stepper photolithography or nanoimprint lithography). The resolution of the display is determined by the size of the subpixels, which are mainly limited by the LCD pixels.

The tunability and flexibility of the nanogratings means that the narrow-band spectra of the display's modulated primaries can be computationally optimized for gamut maximization. Using commercially available LEDs (Fig. 2(a)) and appropriate grating geometries, the following filtered, narrow-band primaries were computed for gamut maximization (Fig. 2(b), which yield the color gamut shown in Fig. 2(c)).

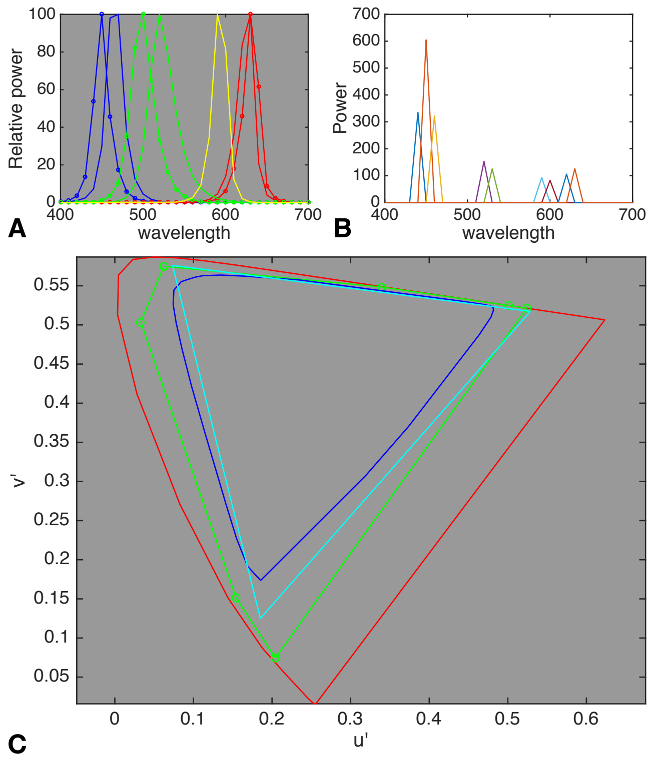

Fig. 2: LED Spectra and basic principle description. (A) Spectral output of six commercial LEDs, (B) optimally selected, spectrally-sharpened primaries (modulating three LEDs from (A)), (C) CIE u'v' color gamuts of all spectra (red), HP DesignJet Z3200 (blue), a wide-gamut display (cyan) and the display using our spectrally-sharpened primaries (green).

Note that in color gamut terms, the result (green curve) significantly exceeds both that of a high-end photo printer, such as the HP DesignJet Z3200, 12-ink inkjet printer (blue curve) and of a commercially available wide-gamut display (cyan curve). Importantly, the resulting gamut also resembles the shape of the gamut of the Object Color Solid (red curve) (Schrödinger, 1920). This also allows for color gamut mapping to preserve color relationships of natural scenes since the relative chromas of the most chromatic colors around the hue circle have ratios close to those of the OCS. This means that disproportional changes are not introduced by mapping to the gamut available in this type of display.

Given primaries as presented above, each display pixel comprises an array of NxN grating subpixels (e.g. 3x3) where each grating scatters a narrowband beam of light of a different color (Fig. 3(a)). For example, a red LED with a peak emission at 600nm and 100nm of Full-Width-Half-Maximum (FWHM) can me modulated into several primaries with peaks at 590nm, 600nm, 620nm, 630nm and FWHM of 10-20nm, giving rise to 4 separate primaries (Fig. 2(b)).

The NxN array of spectrally narrow-band primaries constitutes the basic building block of the nanograting display. To achieve full color variation using these arrays, a masking mechanism is used. The masking mechanism (either an absorptive mask or an LCD) takes a cell of constant layout and, depending on the desired output color of that cell, covers some of the NxN primaries. This masking mechanism can be achieved in a display using liquid crystal cells. With cells of 9 primaries and a binary masking mechanism there are 2^9=512 display primaries, conceptually similar to printer Neugebauer primaries (Fig. 3(a)).

Once the above mechanism for controlling individual subpixels is in place, matching a given target color (e.g., the colorimetry of a source image's pixel) consists in identifying which of the system's 512 display primaries can be convexly combined to match it. Here the convex combination is achieved using the human visual system's limited spatial acuity and therefore is an optical merging of sub-threshold stimulus content. In other words, once a set of display primaries that convexly combine to match a target color are identified, their convex weights correspond to relative area coverages needed by the corresponding primaries. For example, to match a mid-gray on our display requires a 50% coverage by the display primary with the following mask: [1 0 1 0 1 0 1 0 1] (i.e., blocking out the 2nd, 4th, 6th and 8th of the 9 narrowband primaries) and a 50% coverage of another primary with the following mask: [0 1 0 1 0 1 0 1 0] (Fig. 3(b)). To identify which of the 512 display primaries can be used to match each of the colors in the

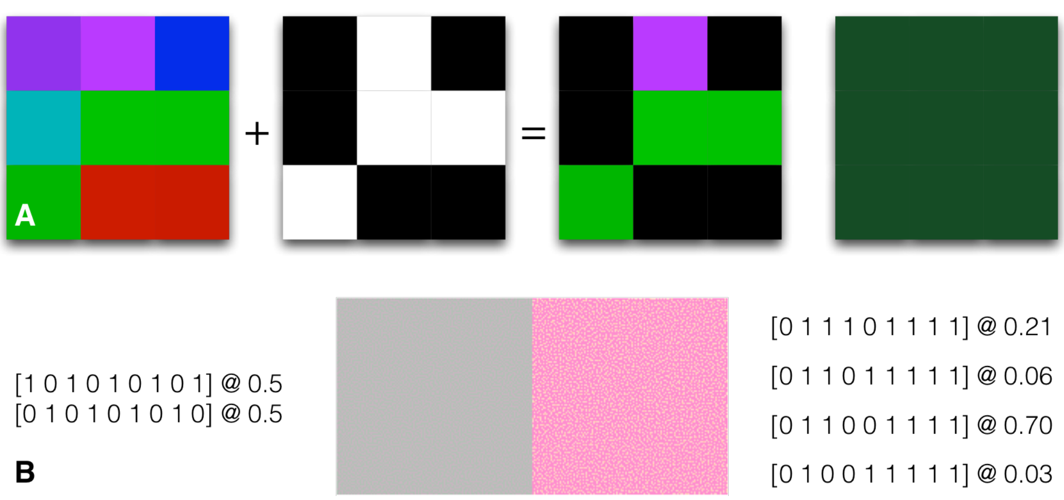

Fig. 3: Primary selection. (A) 3x3 narrow-band primaries, when combined with a mask, yield 512 display primaries, one of which is shown here, (B) combining multiple display primaries via a spatial halftoning results in intermediate colors – two examples are show here with their relative area coverage. The mask shown in this scheme can be either a fixed mask or an LCD.

display's gamut, we use the HANS approach (Morovič *et al.*, 2011).

We compute a traversal of all the polyhedra that can be formed by the display primaries' colorimetries and find, for each of a sampling of the gamut's colors, all the polyhedra that enclose them. The barycentric coordinates of an enclosing polyhedron are then the convex weights with which corresponding primaries need to be combined. The spatial arrangement of the necessary primaries can be achieved using error diffusion or other halftoning algorithms. Such halftoning techniques can be applied to a display due to the compact scale of the sub-wavelength gratings (SWGs), where the side of a 3x3 cell element described above is ~25µm, which is about 4x smaller than a pixel in a high-definition display such as a "retina" Apple iPad that has 264 ppi (~96µm pixel size). This provides an area on the order of ~4x4 pixels in which display primaries can be combined in the proportions dictated by the interpolation weights found by the polyhedral search described above. An alternative approach to exercise control over such a display is the use of LCDs for masking, which allows for a continuous attenuation of the individual SWGs. This would allow for yet finer control and in effect yield the full variety of possible combinations of each of the NxM subpixel primaries at single pixel level, such that if modulation were quantized to 8 bits, $256^9 = 4.7\text{x}10^{21}$ possible signals over a single pixel could be produced and instead of the halftoning (or dithering) mentioned above, the proportional coverages of the primaries determined by the barycentric coordinates for a given color directly determine the intensities of each of the subpixels, then jointly matching the desired color (or spectrum).

Spectral primaries from a single backlight

While the above overview of the sub-wavelength grating display relied on primaries obtained from three LEDs, it is in practice beneficial to use a single, white backlight LED. However, since the above spectral filtering is applicable to any illumination, it can also be used with the white backlights typical of commercial LED displays. To test the performance of the gratings-based filtering, a set of gamut-optimal filters was also computed for for modulating a Thorlabs Warm White LED (Fig. 4).

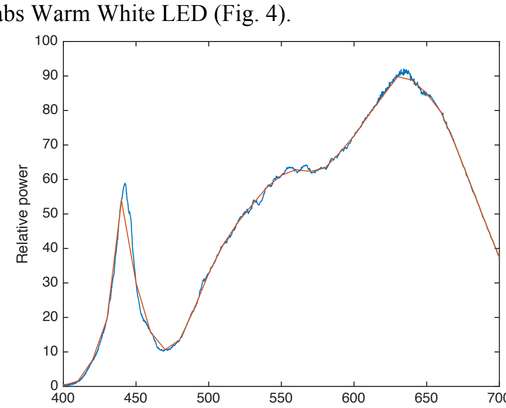

Fig. 4: Spectral power distribution of Thorlabs Warm White LED (MWWHL3): blue shows full Thorlabs data and red a 10-nm sampling interpolated from it.

First, filtered versions of the above light source are computed with 30nm windows and a cut-off is imposed that eliminates primaries whose maximum power is below 20% of the light source's peak power, resulting in 25 filtered primaries (Fig. 5(a)). Note that the filtering here is very simple - a windowing that picks sets of three adjacent 10 nm bands from the light source's spectral power distribution, where the wavelengths either side of the central wavelength are scaled to half their power.

Next, all possible nine-member subsets of the 25 primaries are evaluated in terms of the gamut they give rise to. For each candidate set of nine members this is done by constructing all the 2^9=512 combinations that can be obtained by using between no and all nine primaries at the same time and their convex hull in CIE XYZ is then computed. The set of nine primaries whose convex color gamut, computed in the above way, is largest is then chosen. For the white LED and the filtering parameters used here, the gamut-maximizing choice are the following nine primaries, with peaks at 440, 450, 530, 540, 550, 570, 600, 610, 620 (Fig. 5(b)).

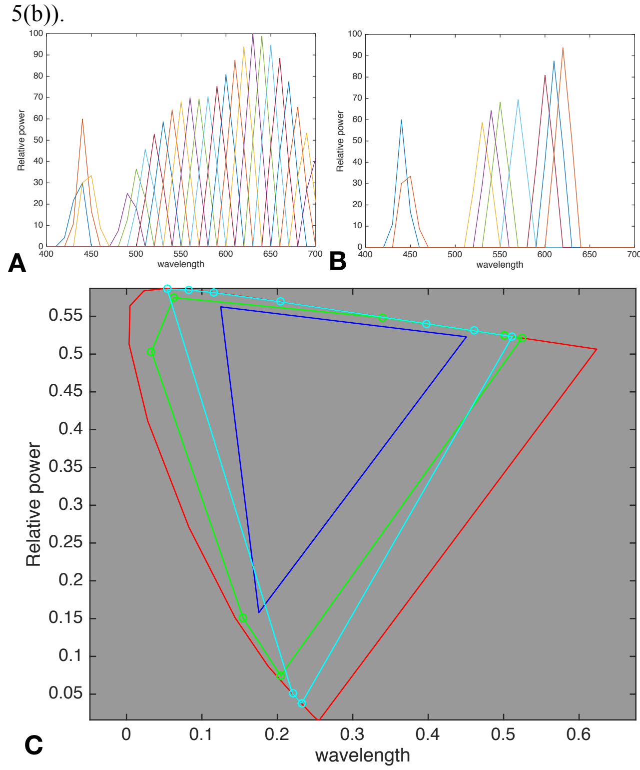

Fig. 5: (A) Filtered primaries obtained from white LED. (B) Gamut maximizing primaries. (C) u'v' color gamuts: optimally chosen primaries (light blue), the spectral locus (red), sRGB (dark blue) and the color gamut of filtering three LEDs - a red, a green and a blue one (green).

Computing the the u'v' chromaticities of these primaries (Fig. 5(c): light blue) and comparing them with the spectral locus (red line), the sRGB gamut (dark blue line) and the color gamut of filtering three LEDs - a red, a green and a blue one, instead of the white LED used here (green line) then results in the following relationships (Fig. 5(c)). The filtered white light results in a smaller gamut in chromaticity terms than the filtered RGB LEDs. In gamut volume terms the result is similar though - the primaries from the white LED resulting in a gamut of $1.93\text{x}10^8$ cubic CIE XYZ units, while primaries that can be obtained from RGB LEDs using the same method gave a volume of $1.97\text{x}10^8$. These relative gamut volumes were obtained by normalizing primary spectra to make the largest power across all wavelengths and primaries be 100 and then computing the convex hull of all their combinations (i.e., primaries, secondaries, tertiaries, etc.). In spite of the smaller chromaticity range, even the primaries from the white light source encloses all but the red sRGB primary and clearly exceed the green and blue primaries in terms of colorfulness.

Test setup

Based on the above simulations, nine 30-nm bandwidth color filters were selected with peaks at the following wavelengths: 440, 450, 530, 540, 550, 570, 600, 610 and 620. To prove the validity of this approach eleven large (2.5 x 2.5 mm) pixels were fabricated and filled with square sub-pixles (10 x 10 µm) separated by 100 µm in both directions. The first nine pixels were made to correspond to the nine computationally selected primaries, and the last two are a combination of two primaries alternating between sub-pixles: 440 plus 620 and 450 plus 530, included to test the convex combination behavior expected in this type of system. Note that this experimental implementation is not intended as a demonstration of a full display system, but rather as a proof of principle of the gratings-based color selection and formation approach.

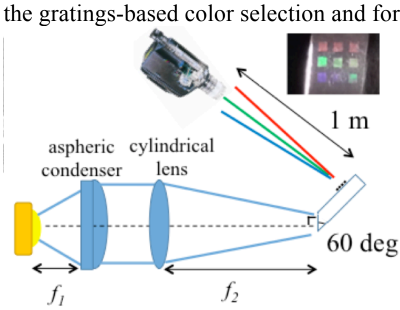

Fig. 6: Experimental setup: Light from a Thorlabs Warm White LED (MWWHL3) is collimated with an aspheric condenser (f1 = 1 inch) and focused with a cylindrical lens with focal distance f2 on to a glass substrate with a side tilted at 60 deg. A colorimeter (Konica Minolta CS-200) is placed 1 m away from the structure to measure the colorimetry of emission.

The experimental setup (Fig. 6) used to test the fabricated sample consisted of a white LED collimated with a short focal distance (f1 = 1 inch) aspheric condenser. A photograph of the sample taken with a low resolution camera is also shown in Fig. 6. A Konica Minolta CS-200 colorimeter was then used to characterize the colorimetry of the light emitted by each of the eleven fabricated pixels and a Photo Research PR-650 telespectroradiometer was used to collect spectral power data.

The camera was placed orthogonally to the sample at a 1 m distance. The light is collected by an aperture angle of 0.125 deg and with an exposure time of 1 sec and. For the light collimation a focal distance of f2 = 20 cm is used.

Results

The spectra of the nine primaries and two combinations of primaries are shown in Fig. 7(a,b) with a 2 nm sampling from 380-780 nm (201 samples) and plotted in relative terms, normalized by peak emission. Also plotted in Fig. 7(a) are the theoretical target peak emissions to show the good correspondence found in measurement while in 7(b) the secondaries (in color) are shown with respect to the constituent primaries (black dashed lines), again showing good correspondence. Representing these spectra in a u'v' chromaticity diagram, and comparing them against existing references, results in Fig. 7(d).

What can be seen is that while in relative terms (Fig. 7(a,b)) the correspondence between the target peaks both for primaries and secondaries is very good, there are significant emissions outside of the peak wavelength range, resulting in less pure spectra. This is partly due to the use of a single 'white' backlight that furthermore is not perfectly flat (Fig. 7(c)) and has pronounced peaks itself. This lack of purity could be addressed by either the use of a flatter single light source, or by using standard off-the-shelf RGB backlights which have already narrower emission ranges that this approach would further narrow by spectral selection. Instead, looking at Fig. 7(d), the first thing to note here is that, with the exception of the green samples (530-570 nm), the mismatch between (very much idealized) simulation and measurements is large in absolute terms. What can also be seen though is the near-linear nature of the combined samples, both of which lie close to the line connecting their constituent primaries (not half-way, which we would only have expected, if the two primaries had the same luminance, but clearly on the line connecting them). Next, it can also be seen that the green samples exceed the sRGB gamut and are close to the HP DreamColor gamut, which is achieved using three, RGB LEDs for the backlight instead of the single, white LED filtered here and used in typical displays.

Another observation to make here is that the 450 nm primary – indicated with a red box – (and to a lesser extent the 600 and 610 nm ones) are inside the convex gamut formed by the other primaries, which means that they don't add anything to the color variety addressable by the system (although they may still be useful spec-

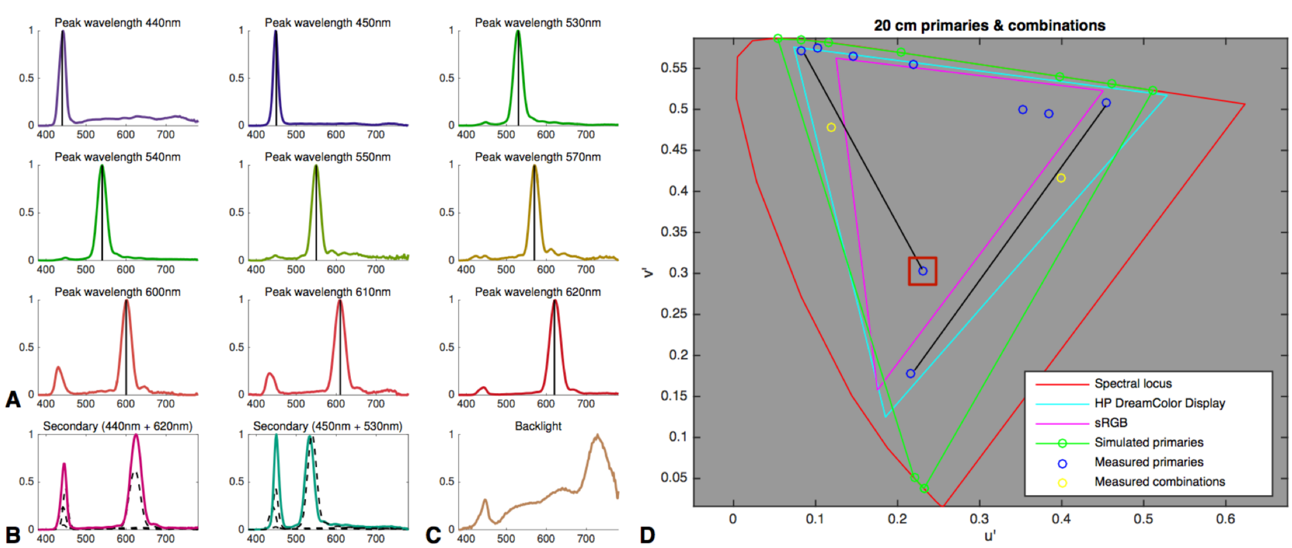

Fig. 7: Relative spectral power distributions as a function of wavelength of (A) primaries vs the theoretical target peak wavelengths, (B) their combinations as secondaries and (C) the unfiltered backlight. (D) u'v' projection of (A) and (B) and comparison against simulated predictions and reference gamuts.

trally).

Conclusions

Overall these measurements show a clear signal that grating color filters provide primaries from a white backlight that significantly exceed the standard, sRGB gamut and even get close in the greens to the HP DreamColor display with its RGB backlights.

Although we don't quantify brightness and energy efficiency of the display, we expect it to be relatively low in this configuration as we use only the light diffracted vertically. However, a more efficient use of the light can be achieved by using an LCD shutter to modulate light diffracted at other angles.

The combination of nanotechnology and advanced color analysis techniques offer a new platform for high quality and scalable large color gamut displays.

References

J. C. Brazas and M. W. Kowarz "High-resolution laser-projection display system using a grating electromechanical system (GEMS)," Proc. SPIE 5348, MOEMS Display and Imaging Systems II, 65 (2004)

cnet (2015) http://www.cnet.com/news/e-ink-turns-one-pair-of-shoes-into-many-shoes/

D. Fattal, Z. Peng, T. Tran, S. Vo, M. Fiorentino, J. Brug, R. G. Beausoleil "A multi-directional backlight for a wide-angle, glasses-free three-dimensional display," Nature 495.7441 (2013)

J. Kwak , W. K. Bae, D. Lee, I. Park, J. Lim, M. Park, H. Cho, H. Woo, D. Y. Yoon, K. Char, S. Lee "Bright and efficient full-color colloidal quantum dot light-emitting diodes using an inverted device structure," Nano letters, 12(5), pp.2362-2366. (2012)

J. Morovič, P. Morovič, J. Arnabat "HANS – Controlling Inkjet Print Attributes Via Neugebauer Primary Area Coverages," IEEE Transactions on Image Processing, 21, 2, (2011)

E. Schrödinger "Theorie der Pigmente von größter Leuchtkraft," Annalen der Physik (Paris), 62, pp. 603-622 (1920)