

A Switched Emissive Transparent Display with Controllable per-pixel Opacity

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Abstract

An emissive transparent display with per-pixel opacity employs rapid synchronized switching of a transparent display and transparent backlight between content with a scattering luminous backlight, and masks with a clear unlit backlight. A 144 fps transparent LCD panel is used in conjunction with a transparent backlight, controllably diffusive smartglass screen, and optional switching background lighting. The display is capable of producing opaque emissive content on a transparent field for novel transparent display and compact spatial augmented reality applications.

Author Keywords

transparent display; opaque; emissive; switching; transparent backlight

1. Objective

Many futuristic display concepts from action and sci-fi movies involve transparent displays with colorfully emissive yet opaque content; we have interest in physically creating such displays. Such a display concept would also be useful in allowing synthetic characters to be visually placed amongst physical objects in a real-world scene, i.e. a compact Pepper's Ghost and spatial augmented reality. In these cases, the ability to control opacity in a transparent display is important, otherwise the content or character would be also appear semi-transparent and low contrast against bright busy background environments.

Practical implementation of such a display is difficult since each pixel of such a display would need not only a color, e.g. red (R), green (G), blue (B) components, and emissive luminance/brightness, e.g. $R,G,B=[0, 1, \dots, 255]$, but also an absorption/opacity, e.g. $\alpha=[0,1, \dots, 255]$. This would be considered a color transparent emissive display with real-world optical alpha (or per-pixel variable opacity). Current displays' pixels control only two out of the three variables (i.e. luminance, color, and opacity). For example, the pixels of a transparent LCD panel vary color and opacity but not emissive luminance; LCD panels do not generate their own light. Similarly, transparent OLEDs may vary color and luminance but do not control opacity; OLEDs do not spatially modulate background light. As a result, content displayed on current transparent displays are low-contrast and semi-transparent. We need pixels that can vary in color, luminance and opacity (e.g. $RGB\alpha$), and the display must be able to accept such four data component signals (or six data component with an independent alpha channel for each color channel). Typical video signals have only three data components, i.e. RGB.

Since common displays are only able to control two out of the three desired variables of luminance, color and opacity, we temporally multiplex opaque-emissive content (color and luminance) and transparency with absorbing masks (tint and transparency). We employ rapid synchronized switching of a transparent LCD display and transparent backlight between displayed content with scattering-luminous backlight, and displayed mask with a transparent - nonluminous backlight states. To implement this scheme, a 120 fps (or greater) transparent LCD panel can be used in conjunction with a variety of transparent backlights.

2. Background

Inspired by transparent display concepts, display manufacturers are producing transparent LCD retail display cases, transparent refrigerator doors, and interactive smart windows as part of their next-generation of novel displays. Currently, these are implemented using LCD panels. See figure 1a. LCD panels aren't self-emissive, so the transparent LCD panel must use the background ambient light as backlight. Furthermore, since transparent and

white content are both presented as white pixels on the display, they have the same transparent visual appearance and light colors are semi-transparent to the background. As a result, the background visually interferes with the displayed content, and the content's appearance changes with different background content and viewpoint. The content, lighting, background, and viewing angle must be carefully considered together. Typically these displays use a brightly lit plain white backdrop to act as a light box for the transparent LCD panel; content typically uses dark colors to appear opaque, or is strategically placed to avoid appearing semi-transparent against physical background objects.

Although research prototypes using transparent OLED panels have been demonstrated, they suffer a related but opposite problem. Since transparent OLED panel pixels only emit light and cannot controllably block background light, their images appear semi-transparent and low-contrast against light-colored backgrounds. See figure 1b. Again their content's appearance is visually affected by the background content and viewpoint. These displays appear best against dark plain backgrounds.

The ideal transparent display would be capable of presenting dark and bright content with controllable opacity. This would allow high contrast, opaque content on a transparent field visually independent of the background. See Figure 1c.

Spatially Multiplexed Content and Masks

We have previously presented displays that can control each pixel's color, luminance, and opacity: Pepper's Ghosts, scrim projections, and transparent OLED displays with transparent LCD masks [1]. These displays spatially multiplex the emissive content and the opacity using a transparent emissive layer (e.g. reflected display, scrim projection, or transparent OLED) and a transparent absorbing layer (e.g. a transparent LCD panel) respectively. While effective, the Pepper's Ghost version requires a large beam combiner creating a large footprint. The scrim projection version has a small physical footprint but needs space for projection throw. Transparent OLED displays with colocated LCD masks have a minimal footprint and allow for direct interaction with the display surface. Unfortunately, current commercial transparent OLED displays (e.g. uTOLED-20-G2, 4D Systems) are limited in size (2" x 2"), and larger research displays (>15" diagonal) are unavailable outside the laboratory. One aim of the presented research is to replicate the abilities and compactness of the transparent OLED display and LCD mask, but instead using larger available transparent LCD panels and backlights.

Temporally Multiplexed Content and Masks

Similarly, the emissive content and the opacity mask can be temporally multiplexed. This requires transparent displays capable of high frame rates to switch between content and mask without flicker. We previously presented a switching dual layer display in which the foreground display contained opaque emissive content on a transparent field, independent of the content on the background display [2]. We rapidly switched between two states: 1) the foreground transparent LCD panel presenting its content with the background display presenting a white field acting as a global backlight; and 2) the foreground display presenting the content mask with the background display presenting its content. The foreground display's pixels exhibit controllable color, luminance, and opacity, but require and depend upon the background display. Another aim of the presented research is to use this switching scheme but without the need for the background display, thus allowing physical backgrounds to be visible behind the switched transparent display and backlight.

Transparent Displays with Transparent Backlights

There are other displays that propose to use a transparent backlight and transparent LCD panel but for different applications and without using a rapid switching scheme. Lindlbauer and collaborators created a see-through display with transparency control for dual sided collaborative interactions (Tracs) [2]. Tracs consists of two transparent displays sandwiching large 9x6 array of individually switchable PDLC diffuser panels with a matching a coarse LED grid backlight layer and a polarization adjustment layer. Sections may be switched between diffusive allowing only the viewer's content to be seen, or transparent allowing their collaborator on the other side of the screen to be seen. The coarse LED point lights in the back layer create uneven illumination, but are mainly present to provide additional back lighting to the LCD panel to complement the ambient background light.

In a patent by Bohn [3], he and collaborators proposed a hand-held phone display that switches between a see-through augmented reality mode and an opaque display mode; publication on a physical practical prototype was not found. The display consists of a three-layer sandwich of a viewer-facing display panel, a transparent backlight assembly, and a “multi-mode” panel. The display panel is a transparent LCD panel or similar. The transparent backlight is described as an edge lit transparent slab with embedded scattering, refractive, or diffractive elements.

The multi-mode panel is envisioned as an active shutter (e.g. LCD), reflector, electrochromic, or electrowetting cell switchable between being opaque or transparent over the entire panel, in sections or pixel-by-pixel, (i.e. a second pixelated display for passing/blocking the background view). The front display panel and middle transparent backlight provide color and luminance, while the rear multi-mode layer provides variable opacity.

The use of a rear multi-mode layer to control opacity, spaced and separated from the display panel by the evenly illuminated transparent backlight creates several issues, including strict layer alignment requirements, Moiré interference and parallax effects between the separated pixelated display and a pixelated multi-mode panel, as well as a dedicated synchronized video input for the multi-mode layer. Furthermore, because the transparent backlight is an evenly lit and non-pixelated sheet between the pixelated front display panel and rear multi-mode panel, the display cannot produce certain content; for example, white opaque content on a transparent unlit field. A white opaque pixel requires the display pixel to be clear, the backlight illuminated, and the multi-mode pixel opaque; while a transparent unlit pixel requires the display pixel to be clear, the backlight unlit, and the multi-mode pixel clear. The backlight is not pixel level controllable, so is either on or off for all pixels in the display. As a result, with any emissive display content present, an ideally clear area would look hazy or milky. In another patent by Bohn [4], a pixel level controllable transparent backlight is proposed using addressable electrowetting cells to selectively out couple light internally reflected in an edge-lit light guide. However, when used in this display’s configuration, there will still be aforementioned alignment, synchronization, Moiré, and parallax effects between the pixelated display panel, pixelated backlight, and pixelated multi-mode layers.

In patents, inventors have proposed various other transparent backlight units including LED edge-lit polymer dispersed liquid crystal (PDLC) panels, and an array of transparent OLED pixels [5], although neither are said to rapidly switch. Any of these transparent backlights, or similar, may work with our switching content/mask scheme, but they must be capable of rapidly switching between opaque illuminated and transparent unlit states. If the transparent backlight panel is always illuminating a transparent LCD panel, as commonly proposed, white and transparent imagery on the LCD panel appears the same – hazy or milky white.

3. Design

Purpose and Procedure

To implement a luminous transparent display with optical alpha, we employ temporal multiplexing of emissive content and opacity masks. We use a combination of a fast frame rate (≥ 120 fps) transparent LCD panel and a synchronized switching transparent backlight. The switching transparent backlight can controllably and quickly change from being luminous and opaque/scattering to being non-luminous and transparent. The display rapidly and continuously alternate between two states:

1. In the first mode (see figure 2a), the transparent LCD panel displays color content, while the transparent backlight is luminous and ideally opaque to the background. Non-luminous pixels are displayed black on the LCD panel (opaque and absorbing) and do not pass the backlight nor background.
2. In the second mode (see figure 2b), the transparent LCD panel switches and displays a silhouette mask of the content on a transparent field, while the transparent backlight switches to its transparent non-luminous state. Transparent LCD pixels are displayed as white, opaque pixels are displayed as black, semi-transparent pixels are displayed as grey, and tinted pixels appear are displayed as their respective colors.

When rapidly alternating between the two modes at 120 Hz or greater, the luminous content and the masked background visually combine without flicker (see figure 2c).

Although the main innovation needed to create the emissive transparent display with optical alpha is the rapid switching between the luminous content and masked opacity modes, we also require a switching transparent backlight. Even though a variety of transparent backlights were mentioned and can be used, we prototyped several new types of transparent backlights that can rapidly switch from being transparent and non-luminous, to being opaque/scattering and luminous including the following:

- a) Projected Switching Scattering Liquid Crystal Panel: A scattering smart glass screen (e.g. PDLC) can switch from being transparent to scattering and visa-versa. Projected light from LED flood spotlights evenly illuminates the smart glass when the LCD panel displays color content and the smart glass is in a scattered state; no light is projected onto the liquid crystal screen when the LCD panel displays the mask and the smart glass is transparent. See figure 3a.
- b) Beam-combiner with Smart Glass Panel: A beam-combiner (i.e. a 45° half-silvered mirror) can be used to direct light from the background scene or from an opaque backlight unit (e.g. a large LED array backlight panel, or even a second monitor) to a transparent LCD panel. A smart glass panel is placed behind the beamsplitter. When the backlight unit is lit, light is redirected illuminating the LCD panel's color content, and the smart glass is made scattering, diffusing the background scene. When the backlight unit is unlit and the LCD panel is displaying the content mask, the smart glass panel is made clear, thus making the masked background scene visible. See figure 3b.
- c) We also independently implemented a transparent backlight using an LED edge-lit particle embedded clear plastic sheet with a backing sheet of switching smart glass. See figure 3c.

Scattering from the PDLC smart glass sheet helps diffuse and veil a bright background that may appear through the illuminated transparent backlight (i.e. edge lit particle embedded plastic). Without the scattering effect of the PDLC, the emissive content simply adds to the background and appears semi-transparent. Alternatively, a ferro-electric shutter or second LCD panel could be used as an electronic shutter to block the background rather than diffuse its light; however size and attenuation currently limit these choices.

Although we built display prototypes using all these types of transparent backlights (and more), for brevity, we only detail the implementation using the edge-lit particle embedded clear plastic with smart glass backlight. Our prototypes using the other types of transparent backlights are similar in the implementation of the display, synchronization, and switching, differing mainly in the details of illumination, the principles (and some implementation details) of which were described above.

Implementation:

A 27" Asus VG278HE 144Hz capable monitor is modified to make a transparent display by removing its backlight and diffuse anti-glare film. Two stacked 15" x 24" pieces of particle embedded acrylic material (Endlighten, Acrylite) are placed flush behind the matching size monitor and edge lit using several backlight LED strips (Samsung) arranged on all edges. An additional 15" x 24" of PDLC smart glass (LTI smart glass) is placed behind the Endlighten material. See figure 4. Various PDLC formulations were tested and one specifically capable of switching from transparent to clear (or visa-versa) at 60 to 144 Hz was chosen. A HPZ800 workstation with a Quadro 2000 graphics card (nVidia) running Bino stereoscopic 3D movie player, takes an over-under content/mask image and outputs OpenGL quad-buffered frame-sequential 1080p alternating content and mask pair at 144 fps over a DVI-link. A custom OpenGL program to create the quad-buffered 144 fps frame sequential content/mask output could also be written for an interactive display.

The display, transparent backlight, and smart glass are synchronized via the input video's vertical synchronization (VSYNC) signal. See figure 5. The DVI-D VSYNC signal is embedded in the DVI's blue component's differential signal. A passive DVI splitter is used to route one video output to the transparent monitor, and the other to a custom DVI VSYNC extractor [6]. The DVI extractor uses a long-tailed pair differential amplifier to difference the two differential blue component signals and output the VSYNC pulse.

A MEGA2560 microcontroller (Arduino) takes the extracted VSYNC pulse as an input trigger to two toggles, outputting two 72 Hz square waveforms each with adjustable phases and duty-cycles. One square wave is input to a TTL switching n-channel MOSFET switching a 60 V voltage applied to the PDLC sheet to make it clear or scattering. Another square wave is connected to the enable pin of the LED strips' controllers to control the transparent backlight illumination. If the application allows it, an optional additional signal provides switching for background lighting synchronized to the display state. The microcontroller also outputs signals driving LEDs for timing and debugging purposes.

When the display is presenting content, the PDLC sheet is scattering and the transparent backlight is illuminated. The PDLC sheet scattering helps diffuse and veil a bright background that may appear through the illuminated transparent backlight. When the display is presenting the silhouette mask, the PDLC is clear and the transparent backlight is not illuminated.

Phasing and duty cycle differences in the PDLC and the LED strip's signals are used to account for transition times in the LCD display and the PDLC sheet. Timing is adjusted so the backlight illumination only occurs when the content on the LCD image fully fills the screen and the PDLC has fully transitioned to its scattering state. Similarly the optional switching background lights are turned on only when the entire mask is presented on the display and the smart glass is clear. The state of the display, backlight, and background lighting are checked using a 1000 fps high-speed camera (Exilim HS, Casio), and the timing is adjusted appropriately. See figure 6.

As an extension to the basic technique, background lighting is also switched to illuminate the background only when the LCD panel is fully displaying the mask and the PDLC panel is clear revealing the background. LED spotlights (PAR38, Phillips) were modified by bypassing the bulb's electronics and directly switching the LEDs using an n-channel MOSFET controlled and synchronized to the VSYNC signal by the microcontroller.

The transparent display prototype was setup to represent what might appear in a transparent display case or smart window application. The content and background set were chosen to show-off the display's abilities of high-contrast colorful animated content with variable transparency against a complicated, colorful background with complex lighting. The background was picked to be a pair of physical black sports shoes with yellow laces on a red platform placed in front of a red, white, and blue flag banner. The shoes, stand and background were lit with two-point lighting from the front and left. The content on the transparent display was created to be an animated rotating soccer ball with a colorful swooshes and motto lettering, and a transient animated colored star burst that zooms in and rotates, fading in and out.

Results:

Figure 7 shows an example image displayed on the transparent display with emissive opaque content on a transparent field. Due to the rapid switching at 144 fps, the image visually appears solid and flicker is not evident. The color image is high contrast and opaque against the bright background and does not change with shifts in viewpoint. The soccer ball and text content exhibits deep solid blacks, the whites are emissive and opaque; the colors in the swoosh and text are saturated. The transparent field is clear revealing the background.

Figure 8 shows three captured frames of animation demonstrating the display's variable opacity capabilities. Variable opacity is controlled by the gray tones of the mask images. In the first frame, all the content appears opaque on a transparent field because the mask frame has a black silhouette mask on a white background. In the

second frame, the soccer ball, swoosh and star grayscale mask are completely opaque but the lettering that extends beyond the star is semi-transparent. This is because the mask corresponding to those portions of the image are grey. In the third frame, the soccer ball, swoosh and letters are opaque but the star is now semi-transparent and attenuating large parts of the background. The mask image is black in the opaque areas, gray in the semi-transparent areas, and white in the transparent areas of the frame. The background is visible but noticeably dimmer in the third frame's semi-transparent areas than in the previously transparent areas of the first and second frame. Also the outline of the star in the third frame is a semi-transparent blue because the content is blue and the mask is gray.

There is a slight haze or milky appearance at the left/right edges of the display. The display is rotated 90 degrees in portrait mode, so the rolling frame updates sweeping left to right. The edge haziness is due to background lighting illuminating the frame even while the PDLC is scattering and the display is transitioning from content to mask. Masking the width of the display may reduce the haziness, thus decreasing the time the transition sweeps just the visible portion of the frame.

On the other hand, when using switching background lights synchronized to the display mask, edge hazing is eliminated and the full frame is viewable. The background lights are timed to be on only when the display is fully showing the mask on a transparent field. Although the background lighting is only on for a short time each frame period, the LED spotlights are able to handle a large peak voltage but low average power to provide sufficiently bright illumination while not appearing to flicker. This works well in applications in which the background lighting is controllable, such as in a display case or controlled room environment

Because the same LCD panel presents both content and mask, they are inherently aligned. Neither image/mask calibration nor homographies are required, and they can't become misaligned if the system is bumped or disturbed. The inherent alignment also makes the display wide angle viewable, since there is no spacing and parallax between the content and mask. Although not implemented here, motion blur of mask and content would be appropriate for moving content.

The background needs to be brightly lit due to the inherent light attenuation through the LCD panel, as well as due to the switching scheme. We overcome the attenuation by using bright backlight and background illumination. In our particular use cases, such as a smart window or placing virtual characters in physical sets, the background lighting can be controlled and well-lit. The use of synchronized switched lighting also helps, since we can time the lights to be extremely bright only for the brief moments when necessary, but overall maintain reasonable illumination levels and power. LEDs can handle the large peak voltages with low average power, and can switch fast enough to provide bright illumination without flicker. Much of the light attenuation is due LCD's use of polarization to create display states, as well as color filters, electronics and light masks. Other absorbing display technologies that do not use polarization, such as electrowetting displays, could be used as alternative display panels with lower light attenuation.

Since only the color content and a matching mask are required, real time rendering and interactive performance is easily achievable. In some cases, color content and masks are inherently created together (e.g. rendered 3D computer generated imagery). We have experience creating such content and mask pairs for interactive applications in our previous spatially multiplexed content and mask displays. Consistent alternation between content and mask images is important to maintain proper synchronization of the display state with the switching backlight and background illumination states. Rendering using a graphics card with quadbuffering is useful in this regard. Quadbuffering is typically used in stereoscopic 3D displays with shutter glasses, in which there are separate front and back render buffers for each of the left and right eye images. Rendering occurs in the back buffers, while the front buffers are displayed, repeatedly and consistently switching between the left and right front buffer images. Once the drawing to the back buffers is complete, the front and back buffers are swapped and the process repeats. This scheme ensures the display of the left and right imagery is synchronized to the shutter glass' state and 120Hz frame rate regardless of varying rendering rates. Here we use quadbuffering to ensure consistent 120Hz switching between content and masks synchronized to the backlight, smartglass and lighting, rather than left and right stereoscopic images.

The display is scalable to large sizes, with the LCD size being the main limitation. The 120Hz LCD panels are currently available commercially in sizes up to 90" - 110" diagonal. Edge-lit particle embedded plastic backlights (which our backlights are based on) are commonly used to evenly illuminate large movie posters and are available in stock sizes up to 80" x120". PDLC sheets have been used for large architectural smart glass windows. The switching speed of PDLC doesn't depend upon its size, since it electrically acts as a parallel plate capacitor with an RC constant independent of its area.

Due to the regular pixilation of the transparent LCD panel, light from the background will be diffracted as it passes through the transparent LCD panel. As a result, very deep background objects may appear to be slightly blurred and bright point-light objects may exhibit star-like diffraction patterns. Diffraction effects, however, are not unique to our display and these effects will occur for any pixelated transparent display panel. Larger HD displays will have larger pixels, thus reducing the diffractive effects of pixilation. In our prototype, these diffractive effects are not noticeable. The display case prototype is not deep enough to exhibit background blurring and we do not have point lights in the scene. The highlights on objects do not exhibit the star-like diffraction patterns. Even in our prototypes that have a room as the background, diffraction effects do not appreciably blur background objects up to 6' behind the panel.

4. Impact

We have created and demonstrated a medium-sized compact transparent display capable of producing high-contrast opaque dynamic content on a transparent field. The display uses high speed switching of a 144 fps transparent display and a switching transparent/opaque backlight built using modified commodity hardware. The content/mask switching scheme provides per-pixel independently controllable luminance, color, and opacity. This switching scheme also gives a practical means of addressing optical transparency in a display using standard RGB video signals. Unlike other proposed transparent displays, this display exhibits inherent alignment between mask and content, is free of Moiré or parallax effects, and avoids the difficulty of manufacturing, alignment, and synchronization of a separate addressable per-pixel backlight or additional "multi-mode" opacity control layer. Although the switching scheme can be used with a variety of proposed transparent backlights, we have also introduced and prototyped several existing and new types. The switching scheme even improves the performance of displays using modified versions of previously proposed transparent backlights. The added control of the display's appearance using optical transparency allows new visual and creative effects, such as compact spatial augmented reality displays, futuristic looking transparent displays, compact Pepper's Ghosts, smart windows and display cases.

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Figures



Figure 1a,b,c. Transparent Displays. a) absorbing (e.g.LCD) b) emissive (e.g.OLED) c) ideal absorbing and emissive.

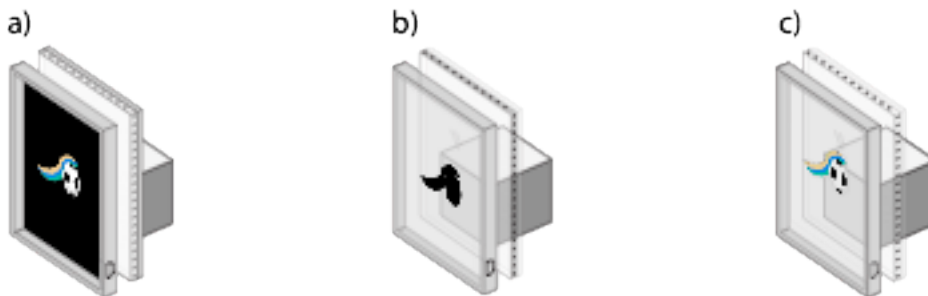


Figure 2a,b,c. Display switching a) content and b) mask with corresponding lit and unlit backlight states. c) rapid switching visually combines content and mask to provide opaque emissive content on transparent field.

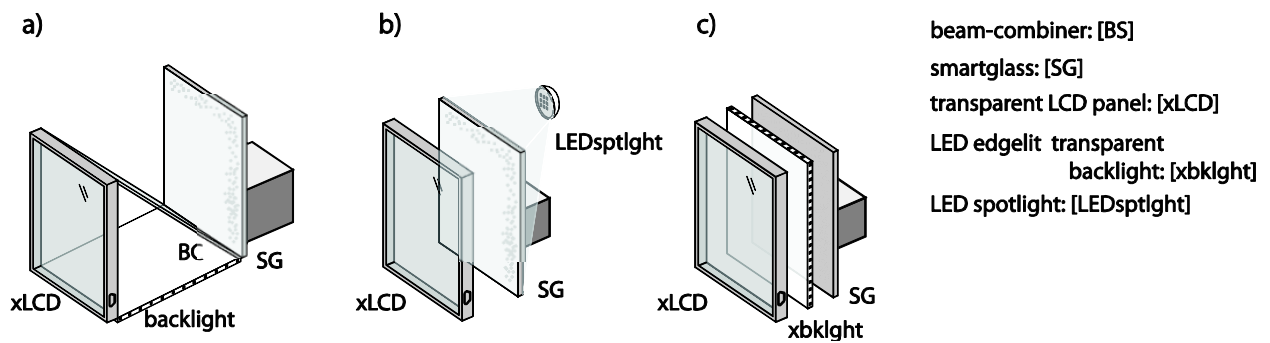


Figure 3a,b,c. Various forms of transparent backlights. a) beamcombined backlight with smartglass, b) projected backlight on smartglass, c) edgelit particle embedded plastic backlight.

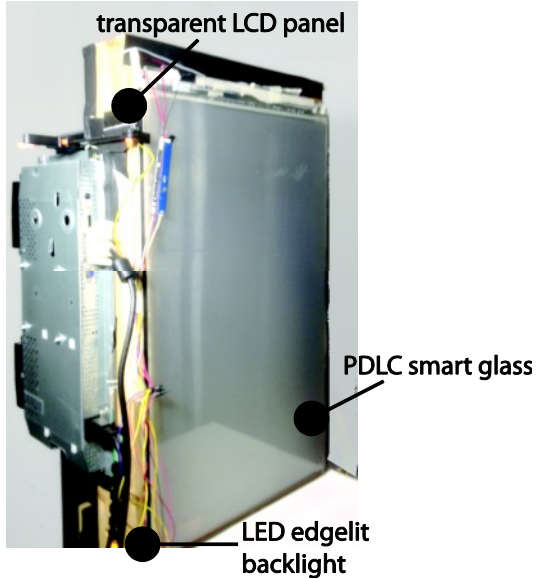


Figure 4. Transparent LCD panel, edgelit acrylic panel and smart glass. (back view)

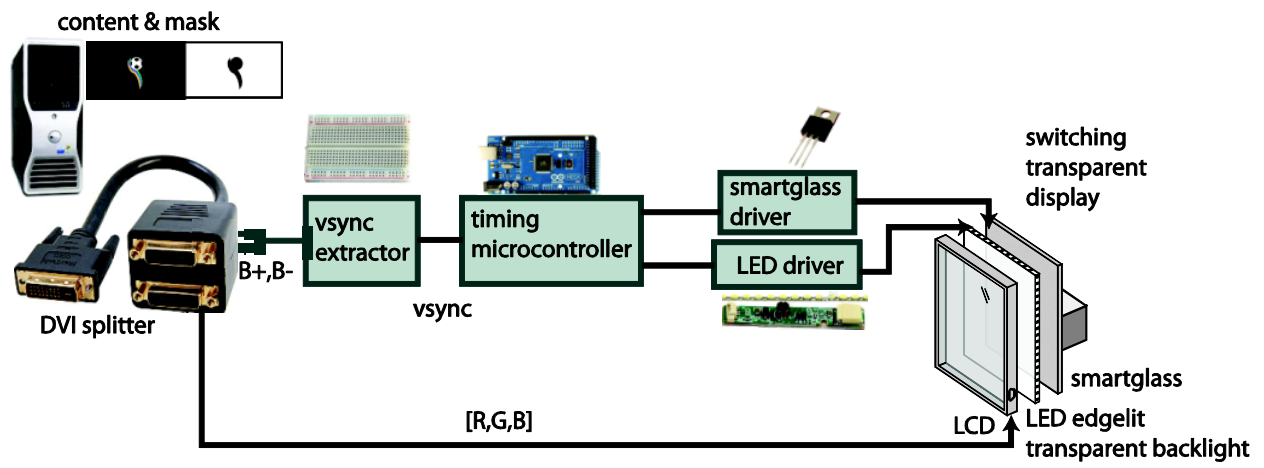


Figure 5. Signal flow

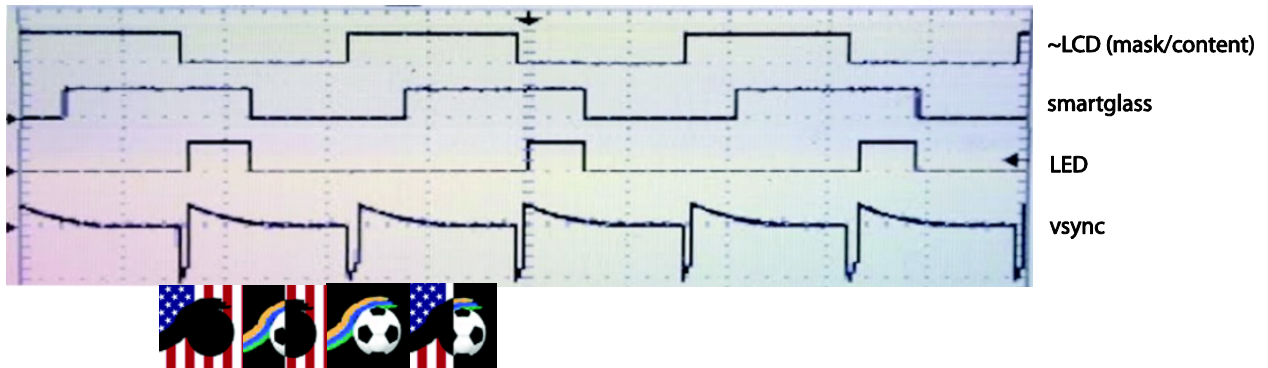


Figure 6. Timing



Figure 7a,b,c. a) Opaque emissive content on transparent field from prototype display. Corresponding b) content and c) mask image frames.

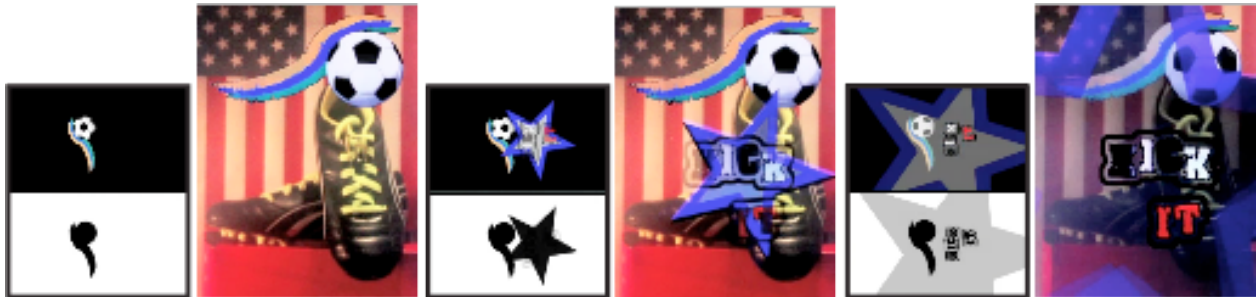


Figure 8. Frames from animation showing variable opacity (captured at 30fps) controlled by grays in the mask frames.