Invited paper: Advanced LC dimmer technology for AR glasses

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Abstract

We introduce the first dynamic liquid crystal dimmer for AR headsets, enabling adaptive ambient light control. The system's segmented dimming capability selectively adjusts display areas to enhance virtual content contrast. This innovation significantly improves outdoor AR experiences by maintaining clear visibility in bright environments.

Author Keywords

Augmented reality; Dimmer; ECB, Dye liquid crystal

1. Introduction

Augmented reality (AR) technology, particularly in optical see-through head-mounted displays (OST-HMDs), faces significant challenges in maintaining the realism of virtual content when superimposed on the physical world [1]. One of the core issues is ensuring that the virtual elements remain visually distinct, even when they overlap with dynamic and complex real-world backgrounds. A critical functionality required to achieve this is occlusion, which involves selectively blocking portions of the incoming background light that might interfere with the visibility of foreground virtual content within the user's field of view (FoV) [2,3]. Without effective occlusion, virtual objects can appear transparent or inconsistent with their physical environment, undermining the immersive experience. Current approaches in the literature have focused on integrating spatial light modulators (SLMs), typically using liquid crystal displays (LCDs), into the optical path of the AR display system [4]. This configuration allows for precise control over the amount of background light reaching the user's eyes, enhancing the contrast and clarity of virtual content. In this paper, we explore an innovative approach to implementing dynamic liquid crystal dimmer technology, designed specifically to provide advanced occlusion control and improve the overall AR experience by dynamically adjusting light transmittance in varying environmental conditions.

2. Key Pixel Design Specification

2.1 Anti-Diffraction Pixel Design

The AR dimmer is composed of a pixelated periodic structure. When users observe the external environment through this optical periodic structure, the transmitted light undergoes diffraction, which in turn degrades image quality. For simplicity, we can represent a one-dimensional optical periodic structure by the following equation:

$$a(x) = \left[\frac{1}{d}\mathrm{comb}\left(\frac{x}{d}\right) \otimes \mathrm{rect}\left(\frac{x}{b}\right)\right] \cdot \mathrm{rect}\left(\frac{x}{Nd}\right)$$

where b is the aperture size and d is the pixel pitch. According to Fourier optics, the diffraction pattern of the transmitted image can be expressed as follows:

$$F\{a(x)\ \ ^2 = \ \ \mathrm{comb}(d\xi) \cdot b \cdot \mathrm{sinc}(b\xi)] \otimes Nd \cdot \mathrm{sinc}(Nd\xi)|^2$$

This derivation can be illustrated in Figure 1. From Figure 1, we observe that to minimize ghost images caused by diffraction, two methods can be considered: increasing the pixel pitch or enhancing the aperture ratio. However, increasing the pixel pitch would reduce resolution, so we employ the second method—enhancing the aperture ratio.

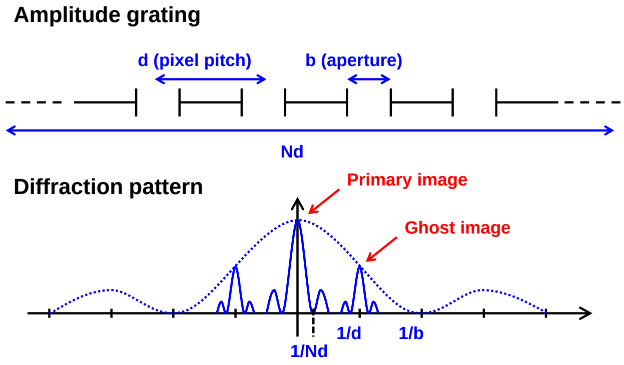

Figure 1. Schematic diagram of the amplitude grating and corresponding diffraction pattern.

2.2 High Aperture Ratio Pixel Design:

Maximizing the aperture ratio is a key factor in achieving high transmittance, which directly impacts the overall brightness and clarity of augmented reality (AR) devices. One critical aspect of this design is minimizing the size of the thin-film transistor (TFT) embedded within each pixel, as a larger TFT can contribute to see-through artifacts and increased haze, degrading image quality by introducing visual noise and reducing contrast. Additionally, the type of TFT plays a crucial role in determining the optical performance, as different TFT types offer varying levels of charge mobility and optical efficiency. The design challenge primarily arises from the relatively large pixel size, which spans several hundred micrometers (μm). This larger pixel size increases the area of the indium tin oxide (ITO) electrode, which in turn requires more charge time to operate effectively. After comparing expected performance metrics, we selected a high-mobility TFT as the optimal choice for the dimming application, as it provides the necessary charge time, supports a higher frame rate exceeding 120Hz, and ensures enhanced optical clarity. The importance of minimizing TFT size and optimizing TFT type to enhance the aperture ratio and reduce optical artifacts is illustrated in Figure 2, which demonstrates how these design optimizations contribute to clearer and brighter display performance.

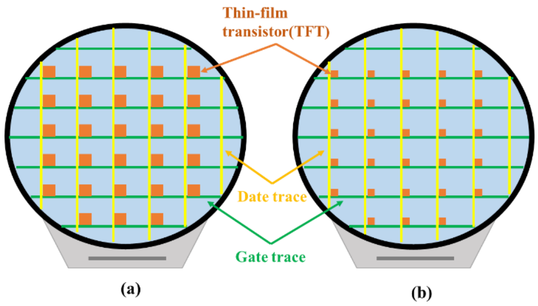

Figure 2. The TFT embedded inside every pixel **(a)** Larger size of

TFT contributes to see through artifacts and haze. **(b)** Minimizing the TFT size to enhance aperture ratio and reduce these optical artifacts.

Furthermore, the presence of horizontal and vertical pixel gap lines can exacerbate these optical artifacts and haze, making the display less transparent and more prone to visual distortion. To mitigate these issues, we reduce the TFT area, as well as minimize the widths of the scan and data lines, and the dimensions of the black matrix (BM). This optimized design effectively increases the aperture ratio, improving transmittance and reducing the visibility of pixel structures and artifacts. Figure 3 illustrates various features between two adjoining pixels, highlighting the design optimizations for source lines and how they contribute to the improved aperture ratio and reduced artifacts.

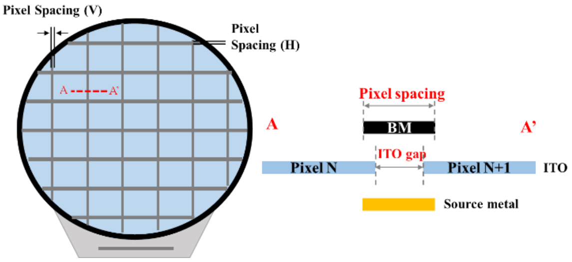

Figure 3. Image illustrating various features between two adjacent pixels for source line

2.3 High Transmittance Pixel Design:

In augmented reality (AR) headsets, achieving higher transmittance is crucial to ensure sufficient brightness across a wide range of lighting conditions. A key challenge in enhancing transmittance is mitigating the impact of opaque layers, such as metal and organic/inorganic insulation layers, which are commonly present in transparent displays, including OLED, Mini LED, and Micro LED technologies. These layers often contribute to undesired color shifts, such as a yellowish tint, and reduce overall transmittance.

To address this, we implemented an optimized etching process to selectively remove unnecessary layers from the transparent areas of the pixel, significantly improving transparency. However, conventional etching techniques, such as dry etching and wet etching, can cause surface damage to the glass substrate, increasing surface roughness and resulting in higher haze values, which degrade visual clarity.

In this paper, we present a dynamic liquid crystal dimmer, designed with multiple optimizations to enhance optical performance and reduce haze. First, by minimizing the number of etching steps in the transparent regions, we significantly reduced substrate damage caused by the etching process. This reduction in surface roughness helps to mitigate haze, thereby ensuring clearer visibility in the AR device. Additionally, the sidewall width in the transparent regions was reduced, further increasing transmittance and minimizing haze, which contributes to improved brightness and image clarity. Furthermore, the optimization of the organic/inorganic insulation layer stack reduced topographical disparities and stress mismatches during the backplane fabrication process. This improvement prevents issues such as photoresist cracking, material residues, and substrate warping, leading to higher manufacturing yields and enhanced device reliability. These collective optimizations result in higher transmittance, reduced haze, and improved process stability, providing a reliable and high-performance visual solution for AR device. The cross-sectional design of the aperture area, highlighting the layered structure and its impact on transmittance, is illustrated in Figure 4**.**

These enhancements enable the dimmer panel to achieve higher transmittance, improved optical clarity, and reduced haze, all while maintaining structural integrity and process efficiency. The result is a more reliable and visually superior AR display solution.

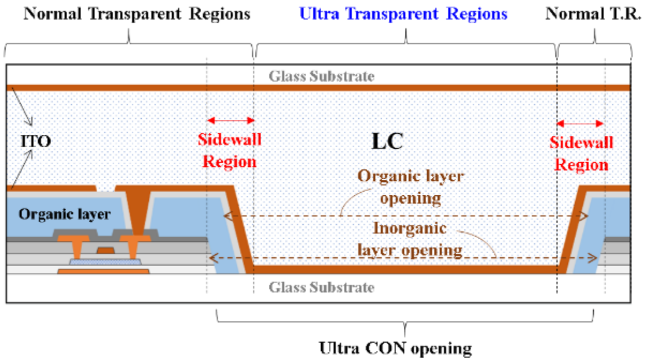

Figure 4. Image illustrating the cross-sectional design of the ultra CON

3. Comparison of Operating Modes

A dimmer can operate in two states: the open state and the close state. In the open state, the dimmer exhibits high transmittance, allowing the user to see the external environment clearly. In the close state, the dimmer blocks external ambient light, enabling the user to view a clear virtual image without interference from background environmental light, as shown in Figure 5.

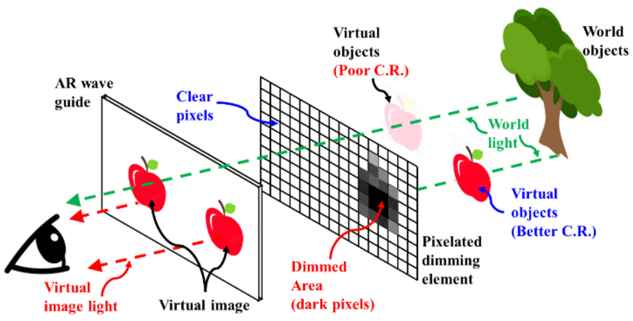

Figure 5. Optical performance of an AR device with active dimmer

There are two primary operating modes for the liquid crystal dimmer : **Dye - Liquid Crystal (LC) mode** and **Electrically Controlled Birefringence (ECB) mode**. Each present unique advantages and trade-offs in terms of optical performance, transmission efficiency, and overall system integration. In this section, we compare the optical properties of these modes and discuss their suitability for different applications in AR systems.

3.1 Electrically Controlled Birefringence (ECB) Mode: Minimizing Diffraction Effects

The ECB mode presents a distinct advantage in terms of minimizing diffraction effects, which are often a concern in liquid crystal dimmers. The electrode design in ECB mode employs a continuous, full-surface indium tin oxide (ITO) layer without patterning, significantly reducing the risk of phase grating effects that could introduce unwanted diffraction artifacts. This makes the ECB mode an ideal candidate for applications where image clarity and minimizing optical interference are critical.

A significant feature of ECB mode is the necessity of polarizers, which, while reducing overall transmission, enable the achievement of an exceptionally dark state. The voltage-transmittance (VT) curve of ECB mode, depicted in Figure 6, illustrates the stable and predictable performance of this mode across a range of operating voltages. The inherent birefringence of the liquid crystal molecules under an applied electric field allows for precise control of light transmittance, contributing to a highly tunable dimming solution.

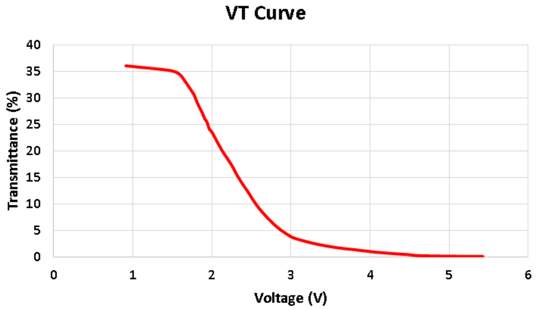

Figure 6. VT curve of ECB mode

Furthermore, the ECB mode can be enhanced by integrating circular polarizers. This combination not only improves the dark state but also provides anti-reflection properties. By incorporating circular polarizers, the dimmer is able to suppress stray light that could otherwise be reflected back into the optical system, a common issue that manifests as glare or unwanted reflections visible to the user. The reflection spectrum of the ECB mode combined with circular polarizers is shown in Figure 7, demonstrating its effectiveness in mitigating reflections and improving the overall optical clarity of the AR system.

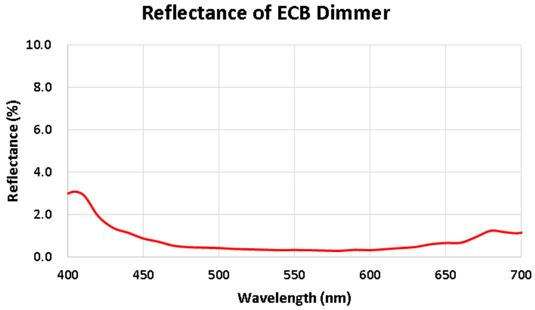

Figure 7. The reflection spectrum of the ECB mode combined with circular polarizers

While the inclusion of polarizers inherently limits the transmission efficiency of the ECB mode compared to dye LC mode, the resulting optical benefits—such as the reduced diffraction and enhanced contrast—make it a superior choice for AR applications that demand high visual clarity and minimal light interference.

3.2 Dye Mode: High Transmission Requirement

The Dye Liquid Crystal (LC) mode is characterized by its ability to maintain a high transmission rate, making it particularly suitable for applications where maximizing light transmittance is critical. In dye mode, the transmission characteristics adhere to the Beer–Lambert law, which governs the attenuation of light through an absorbing medium. The primary constraint in dye LC mode arises from the finite cell gap, which limits the minimum achievable transmission in the dark state. This constraint directly impacts the overall contrast ratio, as the ability to reduce light transmission in the dark state is capped by the inherent properties of the dye and the cell thickness.

The relationship between cell gap and transmission is highly application-dependent. As illustrated in Table 1, adjustments to the cell gap allow for a balance between higher transmission and contrast. For applications requiring enhanced visibility in bright environments, the cell gap can be optimized to achieve higher transmission. Conversely, in scenarios where contrast is prioritized—such as in low-light conditions—sacrificing some transmission to achieve a deeper dark state is possible by reducing the cell gap.

Cell gap(um)	2.82	3.92	4.4
T%_Clear state	56.5%	49.0%	37.2%
T%_Dark state	15.5%	7.1%	0.9%
Contrast ratio	3.6	6.9	40

Table 1. The relationship between cell gap and transmission

Despite these limitations, dye LC mode offers excellent flexibility for applications where a wide range of light transmittance is desired, particularly in environments with fluctuating ambient lighting conditions. However, the trade-off lies in the achievable contrast ratio, which may not be sufficient for applications where high contrast is paramount.

In summary, both Dye mode and ECB mode offer distinct optical advantages, with the choice of mode depending on the specific requirements of the AR system. Dye mode excels in maintaining high transmission, making it suitable for environments with high ambient light, but at the cost of reduced contrast in the dark state. On the other hand, ECB mode provides superior control over diffraction and achieves excellent contrast, particularly when paired with circular polarizers, though its reliance on polarizers reduces overall transmission. The selection between these modes should be guided by the specific needs of the AR application, balancing the trade-offs between transmission, contrast, and optical artifacts.

4. Optical Performance Enhancement

In the development of the dynamic liquid crystal dimmer for augmented reality (AR) applications, several optical design considerations are critical to ensuring optimal performance, including color accuracy, viewing angle consistency, anti-reflection properties, haze reduction, and efficient driving methods.

Yellow Tint Control: Maintaining accurate color reproduction is essential for AR devices, where users must perceive virtual content superimposed on real-world environments with minimal color distortion. One of the challenges is the yellowish tint introduced by the polarizer and the array structure. To mitigate this, precise 0control over the liquid crystal cell gap is necessary. A narrower cell gap promotes higher transmittance of short-wavelength blue light, effectively compensating for the yellow tint and preserving color neutrality. This approach ensures that the AR device maintains accurate color representation across a wide range of ambient lighting conditions.

Viewing Angle Uniformity: To provide a consistent visual experience, it is crucial to minimize brightness variations across different viewing angles. The implementation of a C-plate compensation film in the dimmer’s design helps to address this issue. This compensation film enhances the angular uniformity of the transmittance, ensuring that the brightness remains stable regardless of the observer’s viewing position. By improving the liquid crystal alignment and reducing off-axis light leakage, the C-plate film contributes to maintaining image quality and clarity across a wide range of viewing angles, which is critical for immersive AR experiences.

Anti-Reflection (AR) Treatment: In AR systems, stray light can degrade image quality by introducing glare and unwanted reflections into the optical system. To counteract this, an anti-reflective (AR) coating is applied at the interface between the liquid crystal dimmer and the surrounding air. This coating significantly reduces the reflectivity of external light sources, enhancing the visibility of the virtual content. Additionally, the use of circular polarizers further minimizes reflections and improves contrast without adversely affecting transmittance. By incorporating these AR treatments, the dimmer maintains optical clarity, even in environments with complex or high-intensity lighting.

Driving Method: For safety and performance efficiency, the dimmer is configured to remain transparent in its unpowered state, adopting a normally white (NW) configuration. This design ensures that the AR display maintains transparency when no voltage is applied, providing a seamless view of the real-world environment. To further enhance power efficiency, a compensation film is integrated into the design to shift the voltage-transmittance (V-T) curve leftward. This shift reduces the operating voltage required to achieve the desired dimming effect, thereby lowering the overall energy consumption of the device during active use.

Phase compensation: Innolux has developed an asymmetric quarter-waveplate phase retardation design to compensate for residual phase differences in the liquid crystal layer, a limitation observed in conventional anti-reflective polarizer designs. This results in improved contrast and reduced reflections, enhancing the dimmer’s overall performance in AR applications. The innovative phase retardation design ensures that the dimmer effectively blocks unwanted ambient light, even in bright outdoor settings, surpassing industry standards for AR dimming technologies.

5. Specifications of Active AR Dimmer

Specifications of the avtive liquid crystal dimmer are summarized in Table 2. The dimmer panel provides a high refresh rate with 120 Hz and high Aperture ratio.

Active liquid crystal dimmer	
Pixel size	>500 um
Frame rate	120 Hz
LC mode	ECB (NW)
Aperture ratio	>97%
Grayscale levels	≧256

Table 2. Active LC dimmer specification

6. Conclusion

Innolux’s advanced liquid crystal dimmer technology represents a significant step forward in AR display development. By integrating dynamic dimming capabilities into AR headsets, we provide users with an immersive experience across various lighting conditions. The innovative pixel and optical designs improve both transmittance and contrast, ensuring superior performance compared to existing AR technologies. As this technology evolves, we expect it to enable even more flexible and powerful AR applications, pushing the boundaries of augmented reality experiences in everyday environments.

7. References

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