Latest LC Materials for High-Contrast-Ratio TV and IT Displays

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Abstract

Improved picture quality of Liquid Crystal (LC) Displays is of high demand due to the highly competitive display market. Enhancing the contrast ratio of IPS/FFS technology-based displays is particularly noteworthy, as it can be easily recognized by consumers.

This paper will present the evolution of our UB-FFS LC mixtures, showcase our latest LC materials that achieve record-high contrast ratios, and offer insights into future development directions.

Author Keywords

Liquid Crystal, FFS, IPS, IPS Black, High Contrast, UB-FFS, UBplus, TV, MNT, NB, IT, Merck KGaA, Darmstadt, Germany, EMD

1. Introduction

The performance of electronic displays has steadily improved over time due to significant technological advancements, accompanied by improvement of key parameters like switching speed, contrast ratio, color accuracy, brightness, power consumption, size, and form factor, which altogether enhance the immersion of content experience. Still today, the performance of these parameters characterize premium displays.

From the early days of cathode ray tube (CRT) displays, which only produced monochrome images, to the advent of color displays and larger screen sizes, notable disruptions have shaped the industry. The introduction of Liquid Crystal Display (LCD) technology marked a pivotal shift, enabling slimmer designs with new form factors [1].

Over the years, LCD technology has evolved and enabled larger screens with higher resolutions and diverse form factors, such as curved displays, whilst achieving increasingly thinner profiles and smaller bezels [1].

When looking closer into the LCD technology, it becomes clear that not only one single LCD technology exists, but several sub-technologies [1].

Vertical Alignment (VA) technology including Polymer Stabilized Vertical Alignment (PSVA) technology dominates the large-screen market due to their superior contrast ratio [2,3].

In the IT sector, In-Plane Switching (IPS) technology including Fringed Field Switching (FFS) prevails, as it offers superior viewing angle dependency compared to VA displays [4].

Additionally, the Twisted Nematic (TN) technology needs to be mentioned as the origin of successful commercialized LCD technologies and known for its fast-switching speeds. On the other hand, it shows inferior contrast ratio and viewing angle performance [5]. As a result of these disadvantages, TN displays are becoming less present in the market, clearly indicating that displays with high picture quality will prevail.

The emergence of OLED displays has introduced a new disruption, offering exceptional picture quality characterized by vibrant colors, high contrast ratio, and fast switching speeds. However, challenges remain regarding the longevity and brightness of OLEDs, where LCDs still demonstrate superior performance [6].

High brightness is essential for displays used in environments with significant ambient light. Surface treatment of displays, which optimizes reflection and luminance, plays a critical role in determining ambient contrast ratio. Significant ambient light conditions are clearly not only found outdoors but also in e.g. office settings, where sufficient ambient light contributes to a comfortable working atmosphere and promotes eye health [7,8]. In these environments, LCD displays can deliver superior performance.

Despite their advantages, IPS-type LCD displays face a notable disadvantage in contrast ratio compared to VA LCD displays, highlighting the need for further improvements in this area. This paper will explore the development of new liquid crystal molecules and mixtures that have significantly enhanced the contrast ratio of IPS-type displays, while also addressing the current limitations and challenges that remain.

2. UB-FFS, the perfect solution for high contrast

Contrast is defined as the ratio of the transmittance in the bright state to that in the black state. To achieve optimal contrast ratio, both high brightness and deep black levels are essential. In the realm of IPS technologies, a significant improvement in the transmittance of conventional IPS-type displays was introduced in 1999 using liquid crystals with negative dielectric anisotropy [4,9,10,11,12]. However, the drawback of these materials was their high rotational viscosity and therefore poor switching speed [13,14]. It was not until 2014 that this technology was commercialized using materials from Merck KGaA, Darmstadt, Germany, known as Ultra Bright FFS (UB-FFS) technology, which enabled sufficient fast switching speeds [15].

This technology achieves up to 15% higher transmittance due to the more efficient switching of liquid crystals with negative dielectric anisotropy in a nonuniform electric field, resulting in less scattering in the transmission profile (see Figure 1), particularly at the edges of the electrodes. The increased transmittance and, consequently, the higher bright state makes UB-FFS an effective solution for enhancing the ambient contrast ratio of LCD displays in environments where ambient light is present.

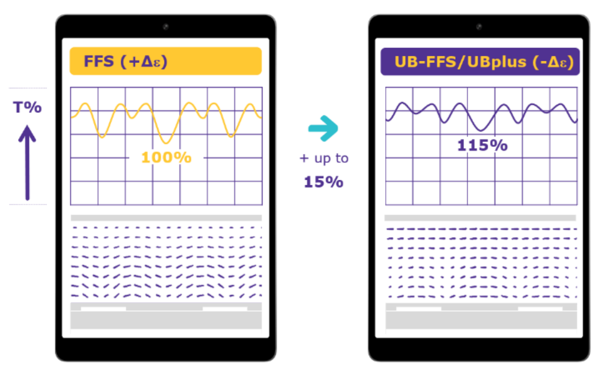

Figure 1. UB-FFS versus FFS Transmittance

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Additionally, UB-FFS can provide a superior black state. Its more efficient switching behavior requires a lower birefringence (Δn) of the liquid crystal mixture compared to traditional FFS for a fixed cell gap (see Figure 2).

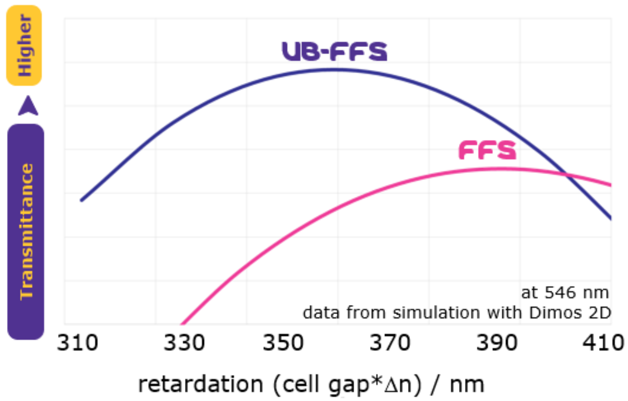

Figure 2. Optimum retardation of UB-FFS versus FFS

A lower Δn is advantageous for achieving a deeper black state, as it improves the black state through decreased scattering parameter (S) (see equations 1 & 2) [16]. The scattering parameter can be divided into S_{Cell} which includes the cell thickness d, and S_{LC} which describes only the liquid crystal contribution.

$$S_{LC} = \frac{\Delta n^2 \cdot (n_e + n_o)^2}{K_{Avg.}} \quad (1)$$

$$S_{Cell} = \frac{\Delta n^2 \cdot (n_e + n_o)^2}{K_{Avg.}} \cdot d \quad (2)$$

S: *Scattering Parameter*
n: *refractive index of the LC*
K: *elastic constant of the LC*
d: *cell thickness of the LC layer*

Furthermore, high elastic constants minimize light scattering, thereby reducing light leakage and enhancing the black level of an IPS-type display [16].

When considering the entire liquid crystal cell, the thickness of the liquid crystal layer (d) also plays a significant role [16]. It is important to note that the ratio between Δn and d must be optimized to achieve the best contrast ratio, balancing high brightness while minimizing light leakage.

Overall, UB-FFS offers a clear solution for advancing the contrast ratio of IPS-type displays by providing higher brightness and deeper black levels.

3. LC Mixture Development

There was a significant delay between the discovery of UB-FFS and its commercialization, primarily due to its slow switching speed. The initial commercialization of UB-FFS occurred in mobile phones and later as UBplus technology in televisions (TVs) featuring enhanced resolution [15, 17]. The increased resolution resulted in a decrease of aperture ratio, finally resulting in a loss of transmittance which could be partially mitigated by UB-FFS/UBplus technology. At that time, the switching speed was just acceptable, which clearly indicated that the goal of new material development for UB-FFS was to identify materials with even faster switching speeds. This pursuit continues today in the field of gaming applications (see section 5). Developing new liquid crystals and liquid crystal mixtures that possess higher elastic constants to enhance the contrast ratio was not in focus at that time.

It took additional years to recognize the contrast ratio advantages of this technology: Continuous advancements in liquid crystals with faster response times enabled the formulation of mixtures with significantly improved, nearly doubled, elastic constants without any negative impact on response time parameter γ_1/K_{11} (see Table 1; response time parameter is γ_1/K_{22}, but K_{22} is empirically considered to be half of K_{11}) [15]. Having mixtures with faster response time parameters allowed the design of LC mixtures with a higher Nematic – Isotropic Phase transition temperature (T_{N-I}) which enables higher elastic constants while having no draw back in response time (see Table 1).

This advancement enabled a tremendous improvement in contrast ratio due to an enhanced black state (see equation 1), while maintaining a similar response time parameter and enabled the IPS Black technology [17].

The challenge here lies in achieving a broader nematic range which is necessary for ensuring a stable product within the specified temperature range.

Table 1. UB-FFS for mobile vs High CR UB-FFS.

Property at 20 °C	Ref. Mixture	High CR Mixture A
T_{N-I}	75.0 °C	122.0 °C
Δn (589 nm)	0.101	0.103
Δε (1 kHz)	-3.7	-3.8
γ_1 / mPas	97	197
K_{11} / pN	13.7	26.9
K_{33} / pN	15.2	23.1
$K_{Avg.}$ / pN	11.9	21.1
γ_1/ K_{11} / pN/mPas	7.1	7.3

4. New LC Molecule Development

The development of High CR Mixture A (see Table 1) marked a significant breakthrough in the performance of IPS-type displays regarding contrast ratio, generating interest in understanding the limitations of contrast ratio for IPS-type displays. Since the LC mixture directly influences the contrast ratio, there is a demand for developing LC mixtures with even higher elastic constants. To achieve this, a new liquid crystal (LC-21-1) was introduced, resulting in an improvement of more than 15% in scattering parameter, while response time parameter improved by approximately 8% compared to High CR Mixture A (see Table 2 and Figure 3). The latest developed LC materials LC-24-1 and LC-21-1 enable an LC mixture (High CR Mixture C) to achieve a scattering parameter improvement of over 20% and a 10% enhancement in response time parameter relative to High CR Mixture A.

Table 2. High CR UB-FFS mixtures with new LCs

Property at 20 °C	High CR Mixture A	High CR Mixture B	High CR Mixture C
New LC	-	LC-21-1	LC-21-1 LC-24-1
$T_{N\text{-}I}$	122.0 °C	120.0 °C	119.5 °C
Δn (589 nm)	0.103	0.101	0.102
Δε (1 kHz)	-3.8	-3.7	-4.0
$K_{Avg.}$ / pN	21.1	24.0	25.0
γ_1/ K_{11} / pN/mPas	7.3	6.7	6.6
S_{LC} / 1/pN	0.0047	0.0040	0.0039

Additionally, it is possible to create mixtures with lower birefringence to further reduce the scattering parameter (see Table 3). However, the impact on contrast is highly dependent on the cell gap and the overall retardation.

Table 3. High CR UB-FFS mixtures with new LCs and reduced birefringence

Property at 20 °C	Mixture B	Mixture C	Mixture B low Δn	Mixture C low Δn
New LC	LC-21-1	LC-21-1 LC-24-1	LC-21-1	LC-21-1 LC-24-1
$T_{N\text{-}I}$	120.0 °C	119.5 °C	127.0 °C	123.5 °C
Δn (589 nm)	0.101	0.102	0.097	0.096
Δε (1 kHz)	-3.7	-4.0	-3.6	-3.7
$K_{Avg.}$ / pN	24.0	25.0	24.6	25.0
γ_1/ K_{11} / pN/mPas	6.7	6.6	8.2	8.0
S_{LC} / 1/pN	0.0040	0.0039	0.0036	0.0035

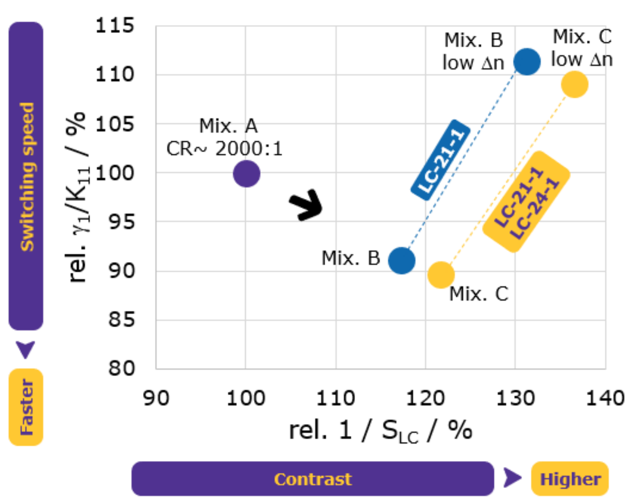

Figure 3. Contrast improvement of UB-FFS LC mixtures

As shown in Figure 3, LC-21-1 and LC-24-1 enable mixture designs with lower scattering parameters due to higher elastic constants and can improve the contrast ratio further while keeping the response time parameter at a comparable level.

Optimizing the LC mixture to achieve higher contrast is an effective strategy for enhancing the contrast ratio of IPS-type displays. With the latest developments in LC materials, Merck KGaA, Darmstadt, Germany, has demonstrated how to increase the contrast of IPS-type displays, by increasing elastic constants and Merck KGaA, Darmstadt, Germany, continuously invests in research to discover even better LC molecules with superior properties, enabling further contrast ratio improvements through optimized liquid crystal mixtures.

A challenge that must and will be addressed in future for developing LC mixtures with even higher elastic constants is the low-temperature stability: The high elastic constants of the LC mixtures cause strong interactions between the LC molecules, which may lead to phase transitions at lower temperatures, transitioning to smectic and crystalline phases.

5. Differentiated solutions for Gaming and TV

High contrast ratio serves as a clear differentiator in front-of-screen performance that customers can easily evaluate and appreciate. Therefore, it is no surprise that these advancements are being utilized not only in high-end monitors but also in gaming displays and large screen displays like TVs.

Each application has its unique requirements, necessitating specific developments and enhancements in liquid crystal mixtures. For instance, gaming monitors demand extremely fast response times, which require low rotational viscosities. In response, Merck KGaA, Darmstadt, Germany, has developed a UB-FFS liquid crystal mixture specifically for gaming (High CR Mixture D in Table 4), achieving high contrast ratio while having a fast response time parameter which is essential within this segment.

Table 4. Differentiated high CR UB-FFS mixtures

Property at 20 °C	High CR Mixture A	High CR Mixture D	High CR Mixture E
Development direction	-	Gaming	Low Vop
$T_{N\text{-}I}$	122.0 °C	79.5 °C	115.5 °C
Δn (589nm)	0.103	0.096	0.103
Δε (1kHz)	-3.8	-3.7	-4.8
γ_1 / mPas	197	77	205
$K_{Avg.}$ / pN	21.1	13.1	24.4
γ_1/ K_{11} / pN/mPas	7.3	4.8	6.9

Other applications, e.g. for Notebook may require lower operating voltages ($V_{Op.}$), Merck KGaA, Darmstadt, Germany, has also addressed this by creating a mixture with increased dielectric anisotropy (designed to reduced $V_{Op.}$) and high elastic constants (High CR Mixture E in Table 4). This enables a high contrast ratio (even a lower scattering parameter than High CR Mixture A) while having lower driving voltages.

In the context of TV applications, the primary challenge for UB-FFS/UBplus is reliability, because rubbed polyimide (PI) is typically used as the orientation layer [18]. In contrast, smaller devices often employ photoalignment technology (UV-PI), which may offer enhanced reliability. As illustrated in Figure 4, an UB-FFS mixture on UV-PI demonstrates slightly inferior reliability compared to a standard FFS mixture on rubbed PI. However, UB-FFS mixtures on rubbed PI exhibits a noticeable degradation in voltage holding ratio (VHR) after backlight exposure, resulting in a lower reliability.

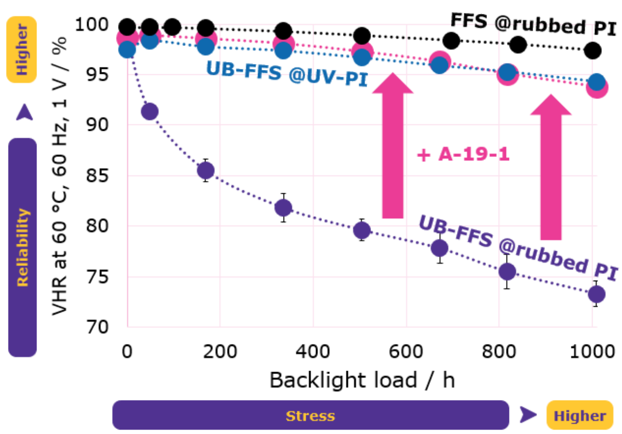

Figure 4. Reliability improvement of UB-FFS LC mixtures

To tackle this challenge, Merck KGaA, Darmstadt, Germany, has developed an additive (A-19-1) that enhances reliability as shown in Figure 4, bringing it to a level comparable to UB-FFS mixtures on UV-PI. This advancement ultimately makes the high-contrast UB-FFS liquid crystal mixture suitable for larger screens, such as TVs.

6. Conclusion and Outlook

History has demonstrated that superior display technologies ultimately prevail. This is also true for UB-FFS, a technology initially developed for higher-resolution displays that now showcases its full potential by providing significantly enhanced contrast ratio in IPS-type displays. Originally adopted in mobile phones, its application has since expanded to IT devices and TVs. With the ongoing development of new mixture concepts that feature a broad nematic range and stability at low temperatures, it is anticipated that this technology will continue to grow and present new opportunities for display manufacturers. For example, it presents significant potential for technologies not yet mentioned such as Head-Up Displays (HUD), offering both improved transmittance and exceptional contrast ratio. However, a key challenge that must and will be addressed is achieving an even higher T_{N-I} and a broader phase stability.

As Merck KGaA, Darmstadt, Germany, is continuously developing new LC molecules to push the boundaries further, stay tuned for updates on the upcoming advancements in liquid crystal molecules and mixtures.

Together with each breakthrough we unlock the potential for more vibrant displays that will enhance our visual experiences in ways we have yet to imagine.

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