

# Fast-response liquid crystals for high image quality wearable displays

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**Abstract:** We demonstrate two ultra-low viscosity liquid crystal mixtures to enable field-sequential-color wearable displays for low temperature operation, while keeping a wide color gamut. Our mixtures offer ~4X faster response time than a commercial material at 20°C and ~8X faster at -20°C. Other major attractive features include: (1) submillisecond response time at room temperature and vivid color even at -20°C without a heating device, (2) high brightness and excellent ambient contrast ratio, and (3) suppressed color breakup with 360Hz frame rate.

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**OCIS codes:** (120.2040) Displays; (160.3710) Liquid crystals; (230.3720) Liquid-crystal devices

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## 1. Introduction

Field sequential color liquid-crystal-on-silicon (FSC LCOS) has been widely used in projection displays, wearable displays including near-eye display (Google Glass), and smart watch [1–3]. By eliminating the spatial color filters, both optical efficiency and resolution density can be tripled. A competitive wearable display should offer high ambient contrast ratio (ACR), low power consumption, compact size and light weight, and wide operation temperature range. To reduce the size and weight, we could replace the bulky and relatively heavy polarizing beam splitter (PBS) by front lighting, but the tradeoff is decreased ACR [4].

For outdoor applications, the ambient temperature could vary from 40°C to –20°C, depending on the geographic location and weather condition. Low temperature operation of FSC LCOS imposes a big challenge because the LC response time increases exponentially as the temperature decreases. With a sluggish LC decay time, the color in the following frame could leak into the present frame and deteriorate the color purity [5, 6]. As reported in Ref [6], a FSC LCOS shows vivid colors at 20°C, but at 0°C its color gamut shrinks dramatically as if it were a quasi-monochromatic display. Moreover, slow LC response time introduces severe color breakup artifact, which also degrades the image quality [7, 8]. A simple solution the LCOS developer takes is to implement a heater to raise the operation temperature, but this approach greatly increases the power consumption [6]. There is urgent need to develop an effective approach to overcome the color mixing issue for next generation wearable displays.

In this paper, we report a simple approach to mitigate the color mixing and color breakup issues by developing an ultra-low viscosity LC mixture. Compared to a commercial LC mixture JC-1041 (from JNC), our mixtures show 4X faster response time at 20°C and 8X faster at –20°C. It overcomes the color mixing issue without using a heating device. Meanwhile, it enables higher frame rate to suppress color breakup. Such a low-viscosity LC helps retain high image quality for wearable displays even at low temperatures.

## 2. Device structure and color mixing

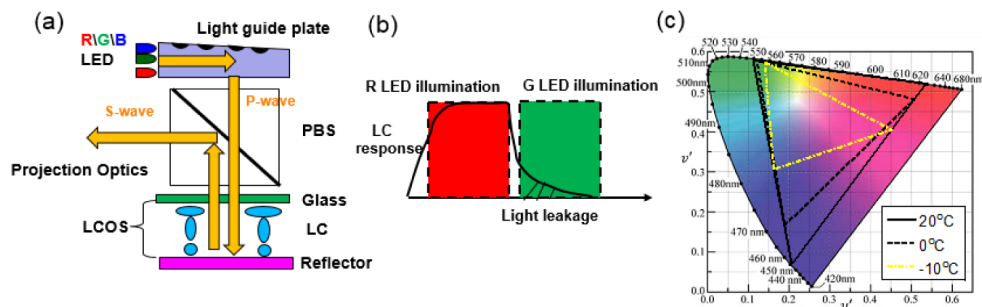


Fig. 1. (a) Schematic of field-sequential-color LCOS module for near-eye display. (b) Origin of color mixing. (c) Shrinkage of color gamut using a commercial LC material (JC1041) at 180Hz frame rate and 90% LED duty ratio.

Figure 1(a) depicts the device configuration of a typical LCOS for near-eye display, such as Google Glass. The R/G/B LEDs are turned-on and -off sequentially to illuminate the LCOS. The light guide plate directs the LED light toward LCOS with uniform spatial distribution. The PBS transmits p-wave while reflecting s-wave. When the light is incident on the LCOS, its polarization state is modulated by the LC layer. Upon reflection from the bottom aluminum reflector, the light is split by the PBS again; s-wave is delivered to projection optics to display image. Grayscale can be easily controlled by the applied voltage.

Figure 1(b) illustrates the occurrence of color mixing. During the transition between color sub-frames (e.g. from red to green), the red field would extend to the green field if the LC response time is too slow. This green light leakage deteriorates the color purity of red, and accordingly reduces the color gamut. Figure 1(c) shows the color gamut shrinkage using JC-1041. As the temperature decreases from 20°C, color gamut shrinks by 21% at 0°C and 62% at -10°C. At -20°C, the [decay time, rise time] of JC-1041 is [3.1ms, 26.4ms], which is significantly longer than a single color frame (5.6ms for 180Hz). Thus, the LCOS cannot be efficiently operated at 180Hz and -20°C. Overall, conventional FSC LCOS suffers from severe color mixing at low temperatures because of the sluggish LC response time.

The LC mode also influences the color-mixing effect. As Fig. 1(b) depicts, LC decay time is more critical than rise time in determining the color mixing. A normally-white LCOS mode, such as mixed-mode twisted nematic (MTN) [9] or film-compensated homogenous cell [10], has faster decay time because of the applied voltage. On the contrary, the normally-black mode, such as vertical alignment (VA), has a much slower decay time because it is governed by the restoring elastic torque. Thus, normally-white mode has less color mixing problem and is preferred for FSC LCOS. In this paper, we focus on three normally-white modes: MTN-90°, film-compensated MTN-63.6°, and film-compensated homogeneous cells.

### 3. Ultra-low viscosity LC materials

The response time of an LCOS is given as  $\tau \sim \gamma_1 d^2 / K\pi^2$ , where  $d$  is the cell gap,  $\gamma_1$  the rotational viscosity, and  $K$  the corresponding elastic constant depending on the LC alignment. As the temperature decreases,  $\gamma_1$  increases exponentially as  $\gamma_1 \sim \exp(E/k_B T)$ , where  $E$  is the activation energy and  $k_B$  the Boltzmann constant [11]. To achieve fast response time at low temperatures, three approaches can be considered: thin cell gap  $d$ , small  $\gamma_1/K$ , and low activation energy  $E$ . Although thin cell gap helps reduce response time [1, 10, 12], a minimal  $d/\Delta n$  value is needed in order to achieve high reflectance. That means, a thinner cell gap should be compensated by a higher birefringence. Indeed, some high  $\Delta n$  LC materials have been reported to improve the response time of a VA LCOS [13]. A big challenge of the thin cell gap approach is its compromised manufacturing yield. Blue phase liquid crystal (BPLC) has also been explored because of its submillisecond response time and insensitivity to cell gap [14, 15]. However, the Kerr constant and response time of BPLC are sensitive to the temperature, especially in the low temperature region [16].

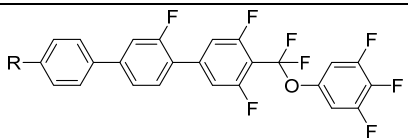
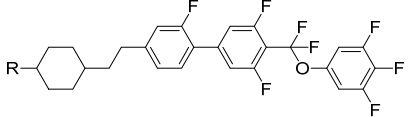
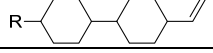
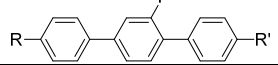
Instead of seeking high  $\Delta n$  materials, we investigated LC mixtures with ultra-low viscosity and low activation energy. Especially, low activation energy significantly suppresses the rising rate of viscosity as the temperature decreases [17]. Therefore, low viscosity and small activation energy are effective for reducing the response time at low temperatures.

To formulate an ultra-low viscosity LC mixture, we prepared some high  $\Delta n$  and large  $\Delta \epsilon$  compounds whose  $\Delta \epsilon$  value is as large as 25. Table 1 lists the chemical structures and compositions of our mixture, designated as UCF-L2. Compounds 1 and 2 have high  $\Delta n$  and large  $\Delta \epsilon$  [18, 19], but their viscosity is relatively high. To lower the viscosity, we added 53% diluters [20] whose structure is also included in Table 1 (#3). For practical applications, an LC mixture should exhibit a wide nematic range and high clearing point, thus we added 22% terphenyl compounds (#4) to widen the nematic range while keeping a relatively high  $\Delta n$ .

In addition to UCF-L2, we also evaluate the LCOS performance using another ultra-low viscosity LC mixture (DIC-LC2) reported in Ref [18]. Table 2 lists the physical properties of

JC-1041, UCF-L2, and DIC-LC2 at three temperatures: 20°C, 0°C, and -20°C. The activation energy  $E$  for each material is also listed in Table 2. It is obtained by fitting the temperature dependent rotational viscosity as described in Ref [17]. Among these three mixtures, JC-1041 has the highest  $\Delta\epsilon$ ,  $\Delta n$ , and clearing point, but its  $\gamma_1/K_{11}$  is also the largest. In addition, JC-1041 has a relatively high activation energy ( $E \sim 370 \text{ meV}$ ), which implies that its  $\gamma_1/K_{11}$  increases substantially as the temperature decreases. In contrast, UCF-L2 and DIC-LC2 have smaller dielectric anisotropy and birefringence, but their  $\gamma_1/K_{11}$  and activation energy are also much lower. From Table 2, the  $\gamma_1/K_{11}$  value of DIC-LC2 is  $\sim 5X$  smaller than that of JC-1041 at 20°C and  $\sim 12X$  at -20°C. UCF-L2 and DIC-LC2 have a lower clearing temperature than JC-1041, but they are still sufficient for most outdoor applications. Among the two low-viscosity materials studied, UCF-L2 has a slightly higher  $\gamma_1/K_{11}$  than DIC-LC2, but its  $\Delta\epsilon$  is also larger so that its operation voltage is lower.

**Table 1. Chemical structures and compositions of UCF-L2; R and R' represent alkyl chains.**

No.	Compound Structure	wt%
1		15%
2		10%
3		53%
4		22%

**Table 2. Physical properties of three LC mixtures studied at  $\lambda = 550 \text{ nm}$  and  $f = 1 \text{ kHz}$ .**

	20°C			0°C			-20°C			$E$ (meV)	$T_c$ (°C)
	$\Delta\epsilon$	$\Delta n$	$\gamma_1/K_{11}$	$\Delta\epsilon$	$\Delta n$	$\gamma_1/K_{11}$	$\Delta\epsilon$	$\Delta n$	$\gamma_1/K_{11}$		
JC-1041	6.1	0.145	15.6	6.6	0.151	28.6	7.0	0.157	110	370	91
UCF-L2	3.1	0.122	3.9	3.7	0.127	7.3	4.2	0.133	14.5	227	80
DIC-LC2	2.0	0.121	2.6	2.5	0.128	4.9	3.1	0.135	9.0	180	75

#### 4. Device simulation

To compare the performance of different LC materials, we first simulated the LCOS with normally-white 90° mixed-mode twisted nematic (MTN-90°) mode [9]. In such a MTN cell, the LC directors are twisted by 90° from top to bottom substrates. To maximize reflectance, the angle between front LC directors and the PBS polarization axis is set at 20°. Thus, MTN-90° modulates the light reflectance by a mixed effect between polarization rotation and phase retardation. MTN-90° is popular in LCOS display due to its high contrast ratio, low operation voltage, small fringe field effect, and no need for a compensation film. For fair comparison, we fixed  $d\Delta n = 220 \text{ nm}$  for all the three LC materials listed in Table 2. For UCF-L2 and DIC-

LC2, the corresponding cell gap is  $d \sim 1.85 \mu\text{m}$ . This cell gap is quite typical for LCOS industry and is easy for mass production.

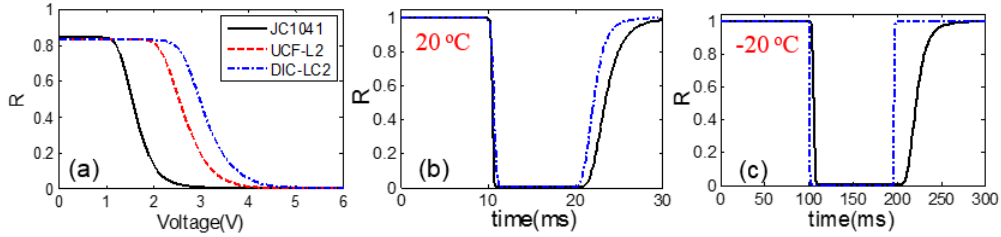


Fig. 2. (a) Simulated VR curves ( $\lambda = 550\text{nm}$ ) of MTN-90° cells using three LC mixtures. (b) and (c) Dynamic response curves of JC-1041 and DIC-LC2 at 20°C and -20°C, respectively.

Figure 2(a) depicts the voltage-dependent reflectance (VR) curves at  $\lambda = 550 \text{ nm}$  for the three LC mixtures studied. They have the same reflectance at  $V = 0$  because their  $d\Delta n$  value is the same, but the dark state voltage is different because their  $\Delta\epsilon$  values are different. There is a clear trade-off between  $\gamma_1$  (response time) and  $\Delta\epsilon$  (operating voltage). For example, DIC-LC2 has the lowest viscosity, but its dielectric anisotropy is the smallest, meaning it needs a higher voltage ( $\sim 5\text{V}$ ) to achieve good dark state. Currently, most LCOS electronic drivers can supply more than 5V, so the operating voltage for DIC-LC2 is still acceptable.

Figures 2(b) and 2(c) compare the dynamic response of JC-1041 (black solid curve) and DIC-LC2 (blue dashed curve) at 20°C and -20°C, respectively. The dynamic response of UCF-L2 is very close to that of DIC-LC2 and therefore not shown in the figure. It is evident that DIC-LC2 has much faster response time than JC-1041, and this advantage is more pronounced in the low temperature region because of its low activation energy.

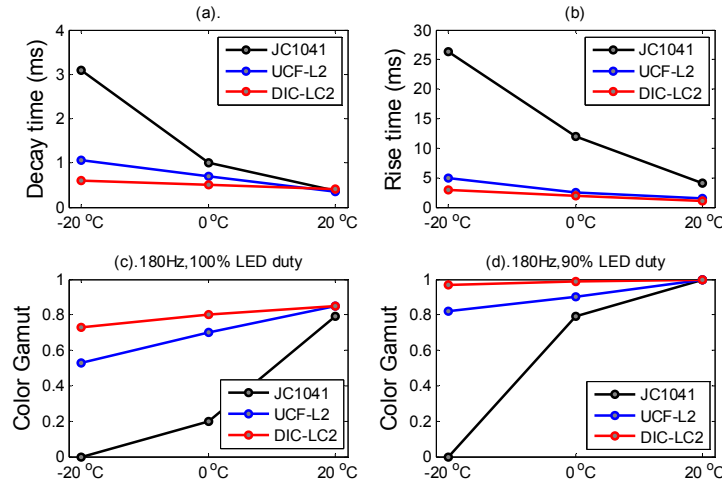


Fig. 3. Temperature dependent (a) decay time and (b) rise time of the three LC mixtures studied. Simulated color gamut for 180Hz frame rate with (c) 100% LED duty ratio and (d) 90% LED duty ratio, respectively.

Figures 3(a) and 3(b) compare the decay time and rise time of the three LC mixtures at 20°C, 0°C, and -20°C. Both rise time and decay time are calculated between 10% and 90% reflectance change. Among these three LC materials, DIC-LC2 has the fastest decay/rise time. At 20°C, its total response time (rise + decay) is 1.52ms, which is 4X faster than that of JC-1041. Moreover, the response time of DIC-LC2 only increases slightly at low temperatures due to its small activation energy. Our UCF-L2 also exhibits similar advantages. By contrast,

the response time of JC-1041 increases drastically. At  $-20^{\circ}\text{C}$ , the total response time of DIC-LC2 is  $\sim 3.55\text{ms}$ , which is 8X faster than that of JC-1041. This dramatic response time improvement is helpful to suppress color mixing and color breakup artifacts.

We also calculated the average gray-to-gray (GTG) response time. The GTG response time of JC-1041, UCF-L2 and DIC-LC2 is  $7.56\text{ms}$ ,  $3.18\text{ms}$  and  $2.59\text{ms}$  at  $20^{\circ}\text{C}$ , but it increases to  $45.56\text{ms}$ ,  $10.28\text{ms}$  and  $6.25\text{ms}$ , respectively, at  $-20^{\circ}\text{C}$ . Although DIC-LC2 has a slightly faster response time than UCF-L2, its operation voltage is higher because of its smaller dielectric anisotropy.

We also simulated the color gamut shrinkage by integrating the LC response curve in the time domain [5]. As Fig. 1(b) illustrates, the light emission at the red color frame would mix with certain green light due to the slow LC response. Accordingly, the effective emission spectrum for the red color frame  $R'(\lambda)$  can be given as:

$$R'(\lambda) = \int_{t_1+(1-m)T}^{t_1+T} R(\lambda)LC(t)dt + \int_{t_2+(1-m)T}^{t_2+T} G(\lambda)LC(t)dt \quad (1)$$

where  $R(\lambda)$  and  $G(\lambda)$  represent the emission intensity spectra of the red and green LEDs,  $LC(t)$  stands for the dynamic LC response curve,  $T$  is the period of each color frame and  $m$  is the LED turn-on duty,  $t_1$  and  $t_2$  represent the start time of red and green color frame ( $t_2 = t_1 + T$ ).

After obtaining  $R'(\lambda)$  we can calculate the color coordinates of the red frame. Equation (1) can be easily adopted to calculate the green and blue color primaries. Thus, we obtain the color gamut coverage under the color mixing effect. During calculation the color gamut is defined in CIE 1976 color space and normalized to the original LED color gamut (without color mixing effect). The emission spectrum of LED is taken from Ref [21].

We first calculate the case for 180Hz frame rate ( $T = 5.55\text{ms}$ ) and 100% LED turn-on duty ( $m = 1$ ). Figure 3(c) shows the color gamut at different temperatures. For JC-1041, the color gamut is  $\sim 80\%$  at  $20^{\circ}\text{C}$ , but quickly shrinks to  $17\%$  at  $0^{\circ}\text{C}$  and  $0\%$  at  $-20^{\circ}\text{C}$ . On the other hand, DIC-LC2 shows  $85\%$  color gamut at  $20^{\circ}\text{C}$  and still maintains  $73\%$  color gamut at  $-20^{\circ}\text{C}$ . Therefore, its LCOS image quality can still be well preserved even at low temperatures.

Reducing the LED turn-on duty  $m$  is another way to suppress color mixing as it increases the temporal separation of each color field [22]. Figure 3(d) plots the color gamut ratio for 180Hz frame rate and 90% LED duty. The temporal separation between the color frames is  $0.56\text{ms}$ . At  $20^{\circ}\text{C}$ , the decay time of all three LC material is less than  $0.56\text{ms}$ , so they can all obtain  $\sim 100\%$  color gamut. However, as the temperature decreases the JC1041 color gamut starts to decline significantly. In comparison, DIC-LC2 can still maintain  $97\%$  color gamut coverage at  $-20^{\circ}\text{C}$ . Usually LED color gamut can cover  $>110\%$  AdobeRGB color gamut, therefore the FSC LCOS can deliver  $110\% \times 97\% = 106.7\%$  AdobeRGB color gamut even at such a low temperature.

Maintaining wide color gamut is critical for wearable display. When using a wearable display under sunlight, the reflected ambient light is also seen as noise by the observer [21]. This also introduces color gamut shrinkage and washes out the image. Our low viscosity LC material can preserve vivid color and crisp image even at  $-20^{\circ}\text{C}$  ambient temperature. This feature can compensate for the color gamut shrinkage and the displayed image is more discernable under sunlight. As a result, our FSC LCOS has superior ambient contrast ratio.

## 5. Higher frame rate

Color breakup is an annoying artifact that degrades the image quality in FSC displays [7, 8]. It manifests itself in the appearance of multiple color images of stationary objects during saccadic eye motion, or along the edges of moving objects when tracking the objects with the eye. Figure 4(a) shows the simulated color breakup when displaying a typical white color. At low frame rate (180Hz), there is discernable rainbow-like artifact at the white object's

boundary. After increasing the frame rate to 360Hz, the color breakup artifact can be significantly mitigated.

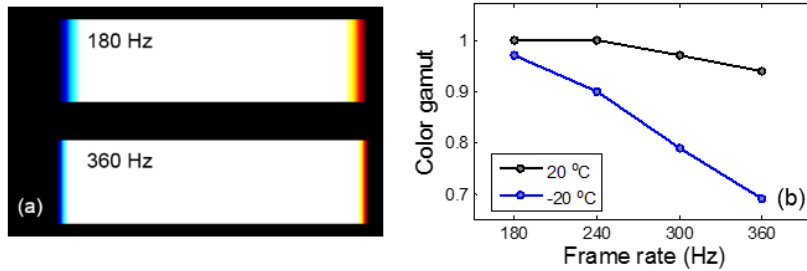


Fig. 4. (a) Simulated color breakup at different frame rates. The white object size is 30 pixels by 150 pixels, and the object moves in a 10 pixels/frame for 180Hz driving. The simulation method is reported in Ref [8]. (b) Color gamut coverage of MTN-90° at different temperatures and frame rates. LC material is DIC-LC2 and LED duty ratio is 90%.

Although high frame rate is effective to suppress color breakup, it reduces the temporal separation between each color frame and accordingly introduces more color mixing effect. For 360Hz frame rate, the period of each frame is reduced to  $T = 2.78\text{ms}$ . JC-1041 is too sluggish to support such a high frame rate, but our ultra-low viscosity LC can overcome this challenge. Figure 4(b) shows the color gamut ratio of DIC-LC2 with increased frame rate. Even at 360Hz, DIC-LC2 can still provide 94% color gamut at 20°C and ~70% color gamut at -20°C. Although high frame rate operation slightly shrinks the color gamut (Fig. 4(b)), it helps suppress color breakup (Fig. 4(a)) and preserve good image quality.

Finally, we investigated the influence of different LC modes. We studied three popular normally-white LC modes: MTN-90°, film-compensated MTN-63.6°, and film-compensated homogenous cell. In MTN-63.6°, the LC is twisted by 63.6° from top surface to bottom substrate. The angle between front top LC director and the PBS transmission axis is 4°. In order to obtain good dark state, a uniaxial compensation film is laminated on the top of LC cell with  $d\Delta n = 15\text{nm}$  and orientated 136° with respect to the PBS transmission axis. In homogenous cell, the LC orientation on the top and bottom surface are in anti-parallel and 45° with respect to the PBS transmission axis. It also requires a uniaxial compensation film with  $d\Delta n = 15\text{nm}$  and oriented at 135° to the PBS transmission axis. Detailed operation principles of these three LCOS modes have been described in Ref [1]. Due to different twist angles, the  $d\Delta n$  value of these three modes is 220 nm, 200 nm, and 185 nm, respectively.

Figure 5(a) depicts the VR curves of these three LC modes. They have similar on-state voltage (~5V). Film-compensated MTN-63.6° and homogenous cells also show slightly higher reflectance at  $V = 0$ . Figure 5(b) compares their color gamut at different frame rates. Film-compensated homogenous cell has the fastest response time due to its thinnest cell gap. As a result, it can maintain 90% color gamut even at 360Hz and -20°C. More strikingly, the decay time and rise time of film-compensated homogenous cell is [0.33ms, 0.61ms] at 20°C and [0.53ms, 1.43ms] at -20°C. This response time is even faster than that of blue phase projection displays [15], while demanding a much lower voltage. A drawback of MTN-63.6° and homogenous cells is that they require a phase compensation film in order to obtain good dark state. As the temperature varies, the dark state voltage would drift slightly because the birefringence of LC changes more quickly than that of compensation film. Despite of this problem, they are still attractive especially when dynamic response is the major concern.

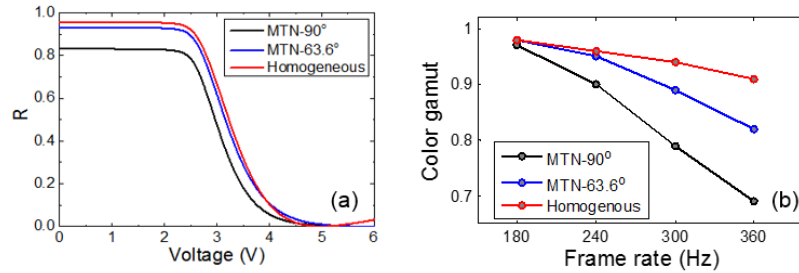


Fig. 5. (a) Voltage dependent reflectance ( $\lambda = 550\text{nm}$ ) of three specified LC modes, and (b) color gamut coverage at  $-20^\circ\text{C}$ . The LED turn-on duty ratio is 90%.

## 6. Conclusion

We have explored two LC mixtures with ultra-low rotational viscosity. These new LCs exhibit several attractive features for wearable displays based on field sequential color LCOS: (1) Submillisecond response time at room temperature while keeping vivid colors at  $-20^\circ\text{C}$ . (2) Low power consumption by avoiding the need of a heating device. (3) High brightness and excellent ambient contrast ratio. (4) Suppressed color breakup with higher frame rate and fast LC response time. (5) Standard LCOS cell gap, which is easy for mass production. This fast-response LCOS is promising for next generation wearable displays.

## Acknowledgment

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