optica

Nematic LCD with motion picture response time comparable to organic LEDs

HAIWEI CHEN,[1,†] FENGLIN PENG,[1,†] FANGWANG GOU,[1] YUN-HAN LEE,[1] MICHAEL WAND,[2] AND SHIN-TSON WU[1,*]

[1]CREOL, The College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA
[2]LC Vision, 4150 Darley Ave. Suite 10, Boulder, Colorado 80305, USA
*Corresponding author: swu@creol.ucf.edu

Received 17 August 2016; revised 23 August 2016; accepted 24 August 2016 (Doc. ID 274001); published 14 September 2016

We demonstrate a fast-response LCD with an ultra-low-viscosity nematic mixture. Its averaged motion picture response time is comparable to that of an organic LED at the same frame rate.

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

http://dx.doi.org/10.1364/OPTICA.3.001033

Liquid crystal displays (LCD) have become ubiquitous in our daily lives [1]; their applications span from smartphones, tablets, vehicles, computers, and TVs to data projectors, just to name a few. Recently, "LCD versus OLED (organic light-emitting diode): who wins?" has become a topic of heated debate [2,–4]. Each technology has its own pros and cons. However, LCDs suffer a $\sim 100\times$ slower response time than OLEDs. Thus, it is commonly perceived that LCDs exhibit more severe motion picture image blurs than OLEDs [3].

To characterize image blurs, motion picture response time (MPRT) [5,6] has been proposed to quantify the visual performance of a moving object, which is normalized to the motion speed. MPRT is jointly determined by the LC (or OLED) response time and thin film transistor (TFT) frame rate. Since the response time of a nematic LCD is much slower than that of OLED, a frequently asked question is: is it possible for LCDs to achieve a comparable or even a faster MPRT than OLEDs?

In this Letter, we demonstrate an ultra-low-viscosity nematic LC mixture in a vertical alignment (VA) cell and achieve an average gray-to-gray (GTG) response time of 1.29 ms by applying a commonly used overdrive and undershoot voltage method [7]. Using these results, our averaged MPRT is 6.88 ms, which is comparable to 6.66 ms for an OLED at a 120 Hz frame rate.

To achieve a fast response time, low viscosity plays a key role. Our strategy to reduce viscosity is to formulate a eutectic mixture with a small but adequate dielectric anisotropy ($\Delta\epsilon$) [8]. Our LC mixture, called MX-40593, consists of some laterally difluorinated two-ring and three-ring compounds, diluters, and alkylbicyclohexyl with a fluorinated tail [9], which helps increase the $|\Delta\epsilon|$ and lower the melting point. The physical properties of MX-40593 at $T = 25°C$ are listed as follows: birefringence $\Delta n = 0.098$ at $\lambda = 633$ nm, $\Delta\epsilon = -2.47$, rotational viscosity $\gamma_1 = 59.5$ mPas, bend elastic constant $K_{33} = 11.9$ pN, and nematic temperature range −40°C to 79.3°C.

In the experiment, we injected MX-40593 into a commercial VA cell with cell gap $d = 3.3$ μm. The measured threshold voltage is 2.1 V_{rms} and the peak transmittance voltage is 6.7 V_{rms} at $\lambda = 550$ nm. To study the GTG response time, we divided the voltage-transmittance curve into eight gray levels equally and measured the response time between different gray levels. As usual, the response time is defined as the time interval between 10% and 90% transmittance. During the measurement, we applied overdrive and undershoot voltages to accelerate the transition process. Table 1 lists the obtained results. According to Table 1, the average GTG response time is 1.29 ms, which is $4.4\times$ faster than the commercial LC (5.69 ms) reported in [3]. Such a fast response time mainly originates from the ultra-low viscosity of our LC mixture and driving scheme. What is more, a low viscosity implies a low activation energy, which leads to a mild increase in the response time even at low temperatures, say, −20°C [10].

Although a fast LC response time is favorable for reducing the MPRT, another equally important factor is the TFT's sample and hold time. Unlike CRT, which is impulse-type display [Fig. 1(a)], both LCDs and OLEDs are hold-type displays [Fig. 1(b)]. MPRT is jointly determined by the material response time and TFT frame rate (f). By a simple convolution of these two factors, the perceived luminance can be obtained, as Fig. 1(c) depicts. Finally, the MPRT is defined as the time interval between 10% and 90% luminance due to the human vision integration effect. The MPRT has been widely used to quantitatively evaluate the image blur [5,6]. CRT is free from motion blur; its MPRT is ~1.5 ms. For a fast-moving object, say, 480 pixels per second, to suppress the image blur to an unnoticeable level, the desired MPRT should be less than 4 ms. As the moving speed increases, the required MPRT should be shortened accordingly.

Figure 2(a) compares our simulated MPRT with the experimental data: the open circles are our data for MX-40593, and the squares and triangles are data from [5]. A good agreement between the simulation and the experiment is found. From Fig. 2(a), we find two important trends: (1) at a given frame rate, say, 120 Hz, as the LC response time decreases, the MPRT decreases almost linearly and then gradually saturates.

Corrected 15 September 2016

Table 1. Measured GTG Response Time of Our VA Cell with Overdrive and Undershoot[a]

	1	2	3	4	5	6	7	8
1		0.58	0.70	0.72	0.93	0.96	1.02	1.37
2	2.73		0.12	0.23	0.34	0.51	0.70	1.14
3	2.81	1.14		0.12	0.27	0.41	0.62	1.05
4	3.56	1.44	0.55		0.13	0.28	0.49	1.01
5	3.73	2.07	1.09	0.54		0.13	0.34	0.98
6	4.07	2.49	1.54	0.92	0.40		0.22	0.87
7	4.23	2.94	2.01	1.41	0.82	0.33		0.69
8	4.61	3.24	2.40	1.84	1.28	0.82	0.39	

[a] $d = 3.3$ μm, $\lambda = 633$ nm, and $T = 22°C$.

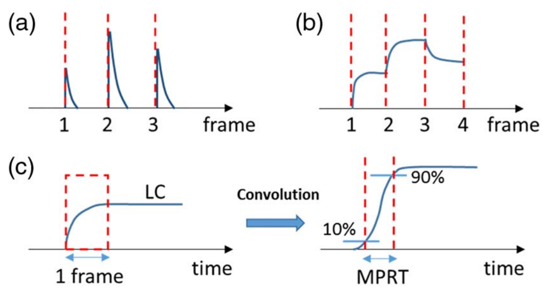

Fig. 1. Schematic diagrams for (a) impulse-type display, e.g., CRT, (b) hold-type display, e.g., LCD and OLED, and (c) MPRT.

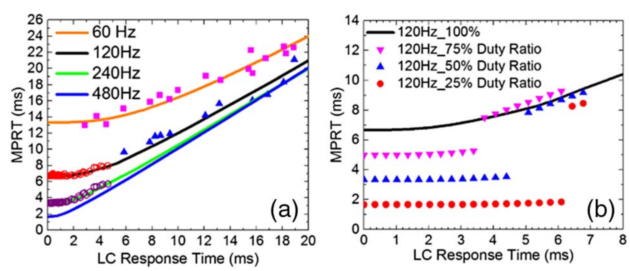

Fig. 2. (a) Simulated (lines) and measured (dots) MPRT at different TFT frame rates. (b) Duty ratio effects on MPRT at 120 Hz frame rate.

For example, the MPRT for an LC with a response time $\tau = 2$ ms is nearly the same as that with $\tau = 0$. So if the GTG response time of an LCD is about 2 ms, then its MPRT is comparable to that of an OLED, even if the OLED's response time is 0. (2) As the TFT frame rate increases, the limiting MPRT (assuming $\tau = 0$) decreases linearly.

To validate the above findings, we measured the GTG MPRT using MX-40593 at $f = 120$ and 240 Hz. The results are listed in Table 2. The obtained average GTG MPRT is 6.88 ms at 120 Hz, while it is 6.66 ms for the OLED [3]. In other words, the LCD and OLED show comparable motion image blurs, except for some slower gray-level transitions, e.g., 8 to 1. If we increase the TFT frame rate to 240 Hz, both the LCD and OLED show much faster but still similar MPRTs (3.71 versus 3.34 ms).

Table 2. Measured GTG MPRT of Our VA LCD at $f = 120$ Hz (top) and 240 Hz (bottom)[a]

	1	2	3	4	5	6	7	8
1		6.70	6.70	6.72	6.72	6.72	6.78	6.78
		3.38	3.40	3.40	3.40	3.42	3.44	3.50
2	7.16		6.68	6.70	6.70	6.72	6.74	6.78
	4.52		3.34	3.36	3.38	3.40	3.42	3.46
3	7.22	6.72		6.68	6.70	6.72	6.72	6.76
	4.58	3.44		3.34	3.36	3.38	3.40	3.44
4	7.72	6.76	6.68		6.68	6.70	6.72	6.76
	5.34	3.52	3.38		3.34	3.36	3.40	3.44
5	7.76	6.80	6.74	6.70		6.68	6.70	6.72
	5.36	3.76	3.40	3.38		3.34	3.38	3.42
6	7.84	6.86	6.82	6.72	6.70		6.68	6.72
	5.52	4.02	3.54	3.42	3.36		3.36	3.40
7	7.90	7.04	6.82	6.78	6.76	6.70		6.70
	5.64	4.32	3.76	3.50	3.34	3.36		3.40
8	7.96	7.28	7.00	6.82	6.96	6.92	6.86	
	5.70	4.68	4.20	3.82	3.48	3.44	3.36	

[a] $d = 3.3$ μm, $\lambda = 633$ nm, and $T = 22°C$.

Another approach to reduce the MPRT without increasing the TFT's frame rate is to decrease the duty ratio (for LCDs, it is the on-time ratio of the backlight), as plotted in Fig. 2(b) for $f = 120$ Hz. As the duty ratio decreases, the effective MPRT decreases linearly, but an obvious tradeoff is the reduced brightness.

In conclusion, we have developed an ultra-low-viscosity nematic LC mixture and achieved a comparable MPRT to OLEDs. These new LCDs would greatly suppress the image blurs. Their widespread applications in TVs and emerging virtual reality and augmented reality displays are foreseeable.

Funding. Air Force Office of Scientific Research (AFOSR) (FA9550-14-1-0279).

†These authors contributed equally to this work.

REFERENCES

1. M. Schadt, Jpn. J. Appl. Phys. **48**, 03B001 (2009).
2. Y. Ukai, SID Symp. Dig. Tech. Pap. **44**, 28 (2013).
3. J.-K. Yoon, E.-M. Park, J.-S. Son, H.-W. Shin, H.-E. Kim, M. Yee, H.-G. Kim, C.-H. Oh, and B.-C. Ahn, SID Symp. Dig. Tech. Pap. **44**, 326 (2013).
4. Z. Luo, D. Xu, and S. T. Wu, J. Disp. Technol. **10**, 526 (2014).
5. Y. Igarashi, T. Yamamoto, Y. Tanaka, J. Someya, Y. Nakakura, M. Yamakawa, Y. Nishida, and T. Kurita, SID Symp. Dig. Tech. Pap. **35**, 1262 (2004).
6. J. Someya and H. Sugiura, J. Soc. Inf. Disp. **15**, 79 (2007).
7. S. T. Wu, Appl. Phys. Lett. **57**, 986 (1990).
8. F. Peng, Y. Huang, F. Gou, M. Hu, Z. An, and S. T. Wu, Opt. Mater. Express **6**, 717 (2016).
9. M. Wand, "Liquid crystals having cyclohexyl core structures and fluorinated tails," U.S. patent 8,778,223 B2 (July 15, 2014).
10. H. Chen, F. Peng, Z. Luo, D. Xu, S. T. Wu, M. C. Li, S. L. Lee, and W. C. Tsai, Opt. Mater. Express **4**, 2262 (2014).