Liquid Crystals, 2015
Vol. 42, No. 12, 1730–1737, http://dx.doi.org/10.1080/02678292.2015.1061714

Flexoelectric effect and human eye perception on the image flickering of a liquid crystal display

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(*Received 26 May 2015; accepted 9 June 2015*)

We investigated the flexoelectric effect of a fringe field switching liquid crystal (LC) cell and characterised the resultant image flicker with different LC mixtures at different frame rates. Incorporating with human eye perception of 10 observers, we found that LC mixtures with a dielectric anisotropy smaller than ~7 lead to unnoticeable image flicker at 60 frames per second. The obtained flicker sensitivity line serves as important guidelines for optimising LC materials and display devices.

Keywords: liquid crystal display; fringe field switching; flexoelectric effect

1. Introduction

Thin-film transistor (TFT) liquid crystal display (LCD) is ubiquitous nowadays; its applications cover from televisions, computers, smart phones, tablets, to car navigators.[1] Among many LC modes developed, fringe field switching (FFS) has become the main approach for mobile displays.[2–5] The device configuration of an FFS cell consists of patterned pixel electrodes and a planar common electrode, separated by a thin passivation layer. In the voltage-off state ($V = 0$), the LC directors are homogeneously aligned. As the voltage increases, the LC directors are gradually reoriented by the electric field, leading to a bright state. Since the electric-field-induced molecular reorientation takes place primarily in the horizontal direction, FFS mode exhibits some outstanding features, including high-transmittance, wide-viewing angle, weak colour shift and robust to touch pressure.[4–6] Both positive (p-FFS) and negative (n-FFS) dielectric anisotropy ($\Delta\varepsilon$) LC materials can be used in FFS.[5–8] Each mode has its own pros and cons. For example, for a given $|\Delta\varepsilon|$ value, positive LCs have an ~ 2X lower viscosity so that p-FFS has a faster response time than n-FFS, provided that the cell gap remains the same. This advantage is amplified to ~5X at low temperature (–20°C).[6] On the other hand, n-FFS has higher transmittance, single gamma curve and unnoticeable image flicker because the LC directors are more uniformly reoriented by the electric field.[7,8] For TFT LCDs, the common materials employed are rod-like low-molecular-weight nematic LCs; [9–11] while other kinds of LCs, such as bend-core molecules, [12,13] are rarely used because of their high viscosity and flexoelectricity. Thus, here we focus on rod-like low-viscosity nematic LCs.

Image flickering is an important issue as it affects the visual quality of a display device.[14] For example, Apple iPhone 6 uses two-domain n-FFS in order to improve the transmittance and viewing angle, while reducing image flickering and colour shift. Several factors can cause image flickering, like TFT leakage current and inadequate voltage holding ratio, but the dominant factors are flexoelectric effect (FEE) of the LC and human eye perception. Until now, there are only a few studies on this effect in FFS cell, and most of the previous reports concentrate on the observation and confirmation rather than understanding the detailed physical mechanisms.[14–16] Thus, a systematic study to understand the mechanisms, quantify the effect and then find solutions is urgently needed.

In this paper, we investigate the FEE of FFS cell systematically. Its origin can be described by the Gibbs free energy. We evaluate the image flicker of FFS cells with different $|\Delta\varepsilon|$ LC materials and different frame rates. Our experimental results indicate that keeping $\Delta\varepsilon \leq 7.2$ could suppress the flicker to unnoticeable level at 60 frames per second (fps). Incorporating with human eye perception of 10 observes, we obtain a flicker sensitivity line for FFS cell, which serves as important guidelines for optimising LC materials and display devices.

2. FEE of FFS LC cell

FEE was first discovered and analysed by Meyer [17] and experimentally observed by Schmidt et al. [18]; it is a kind of interaction between LC and external force (e.g. mechanical stress or electric field). Different from conventional dielectric coupling, FEE still exists even when the dielectric anisotropy of the LC is zero

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*Corresponding author. Email: swu@ucf.edu (e.g. bent-core structures [12,13]). According to Meyer's analysis, the polarisation induced by FEE is as follows:

$$\vec{P}_{\mathrm{f}} = e_{11}\vec{n}(\nabla\cdot\vec{n}) + e_{33}(\nabla\times\vec{n})\times\vec{n}, \tag{1}$$

where e_{11} and e_{33} are flexoelectric coefficients, and $\vec{n}$ is the unit vector of the LC orientation. From Equation (1), e_{11} and e_{33} are the two dominant factors governing the splay and bend deformations. Some methods for measuring e_{11} and e_{33} have been developed, although they are not simple.[19–22] In general, FEE is strong in a system whose molecules possess a large shape polarity as well as a large permanent dipole moment, which means there is a correlation between flexoelectric coefficients and dielectric anisotropy.[17,19]

In an FFS cell, the electric field is strong and non-uniform in both lateral and longitudinal directions. As a result, the rod-like LCs are splayed and bent, which in turn causes a non-negligible flexoelectric polarisation. Thus, the total Gibbs free energy consists of three terms: elastic, dielectric and flexoelectric [23]:

$$F_{\mathrm{Elastic}} = \frac{1}{2}K_{11}[\nabla\cdot\vec{n}]^2 + \frac{1}{2}K_{22}[\vec{n}\cdot(\nabla\times\vec{n})]^2 + \frac{1}{2}K_{33}[\vec{n}\times(\nabla\times\vec{n})]^2, \tag{2}$$

$$F_{\mathrm{Dielectric}} = -\frac{1}{2}\varepsilon_0\Delta\varepsilon[\vec{n}\cdot\vec{E}]^2, \tag{3}$$

$$F_{\mathrm{flexo}} = -[e_{11}\vec{n}(\nabla\cdot\vec{n}) + e_{33}(\nabla\times\vec{n})\times\vec{n}]\cdot\vec{E}, \tag{4}$$

$$F = F_{\mathrm{Elastic}} + F_{\mathrm{Dielectric}} + F_{\mathrm{Flexo}}, \tag{5}$$

where F_{Elastic} is the Frank elastic free energy density, $F_{\mathrm{Dielectric}}$ is free energy associated with dielectric coupling, F_{Flexo} is the free energy contributed from flexoelectricity, K_{11}, K_{22} and K_{33} are the splay, twist and bend elastic constants.

In an FFS cell, the electric field is not uniform in both lateral and longitudinal directions. As a result, finding analytical solution for the total Gibbs free energy (Equation (5)) is rather complicated. Moreover, the image flicker also depends on the human eye sensitivity. Thus, we are taking the experimental approach to establish correlations between image flickering and LC material properties and TFT frame rate. Our objective is to suppress flicker to unnoticeable level.

From Equation (4), the flexoelectric polarisation is dependent on the polarity of the electric field. In a TFT-LCD, both positive and negative voltage frames are alternating in order to keep zero DC voltage. When the applied electric field is reversed (e.g. from positive to negative frame, or vice versa), from Equation (4) the flexoelectric polarisations will be against the new electric field, leading to increased free energy density of the system. To lower the free energy density, the LC molecules will reorient slightly to form another stable configuration. During this polarity transition, the transmittance will change accordingly. When the electric field restores back, another optical transition occurs. Thus, image flickers will arise with fluctuating transmittance when the polarity of electric field is altered regularly, as shown in Figure 1a.[14,15]

Another evidence of FEE in an FFS cell is the difference of spatial transmittance between positive and negative voltage frames, as depicted in Figure 1b.[15,24] In the positive frame, the minimum transmittance occurs on the top of patterned electrodes, but it shifts to the middle of electrode gaps during the negative frame. This clearly confirms the dynamic transition of LC director distributions caused by the flexoelectric polarisation.

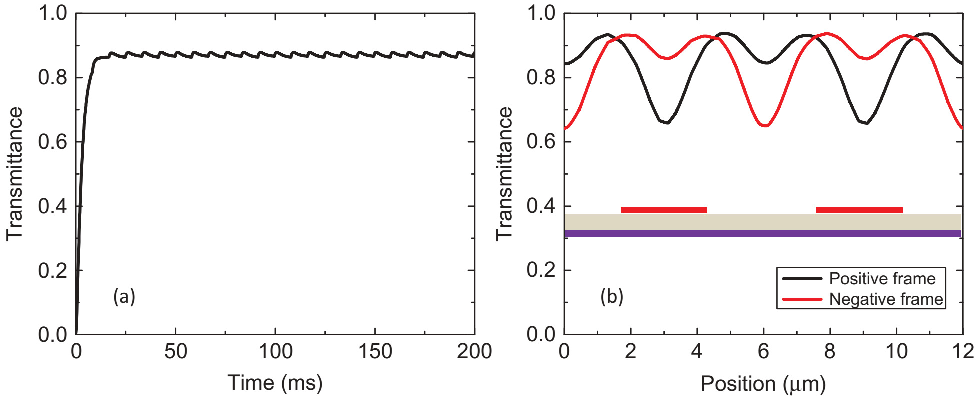

Figure 1. (a) Simulated dynamic transmittance for alternating electric fields. (b) Simulated spatial transmittance distribution of positive and negative voltage frames. LC: Δe = 7.2, e_{11} = 15 pC/m and e_{33} = 15 pC/m.

3. Experimental results

In experiment, we investigate FEE from different influencing factors, including driving frequency, dielectric anisotropy, viscosity and human eye sensitivity. An FFS cell with electrode width w = 3 μm, electrode gap l = 4 μm and cell gap d = 3.5 μm was employed. Also, five different LC mixtures were chosen to investigate the FEE, and their physical properties are listed in Table 1. Here, we define a flicker parameter as $F = \Delta T/T = (T_{\max} - T_{\min})/T_{\text{ave}}$ to quantify the transmittance change during frame inversion.

Figure 2a shows the measured voltage–transmittance (VT) curves for two LC mixtures with different dielectric anisotropies ($\Delta\varepsilon = 10$ and $\Delta\varepsilon = 4.4$). With a smaller $\Delta\varepsilon$, both on-state voltage and peak transmittance increase.[6] Next, we investigated the voltage-dependent image flicker for both materials, as shown in Figure 2b. They exhibit a similar trend: as the operation voltage increases, the image flicker decreases first and then climbs up. In the low grey-level region, although the image flicker (quantified by the F-value) seems large (because of small denominator), the actual ΔT is relatively small. As a result, the flicker is hardly noticeable. In the middle grey-level region, T increases more rapidly than ΔT, resulting in a decreased F-value. However, this condition is reversed in the high grey-level region. Thus, in the following sections, we will evaluate image flicker at the on-state voltage, i.e. peak transmittance.

Table 1. Physical properties of different materials.

	$\varepsilon_{//}$	$\varepsilon_{\perp}$	$\Delta\varepsilon$	Δn	γ_1 (mPa·s)	T_c (°C)
MLC-6686	14.5	4.5	10.0	0.098	102.0	71.0
UCF-M1	10.8	3.6	7.2	0.099	58.1	77.9
UCF-M2	7.3	2.9	4.4	0.100	50.4	80.1
UCF-M3	6.2	2.7	3.5	0.103	45.1	77.9
ZOC-7003	3.6	8.0	−4.4	0.103	101.0	79.0

Note: T = 23°C, λ = 550 nm and f = 1 kHz.

3.1. *Frequency effect*

For mobile displays, 60 fps is the standard driving frequency. A lower frame rate helps reduce power consumption, but the flicker gets worse.[14,15] Thus, image flicker caused by FEE is closely related to the driving frequency. Figure 3 shows the relation between flicker and frequencies. Clearly, as driving frequency decreases from 960 fps to 4 fps, image flicker gradually increases from 5% to 23%. The explanation is as follows: for a higher frame rate, each frame has a shorter duration, which is insufficient to stabilise the LC reorientation. Thus, the dynamic transmittance profile is like a pulse. The higher the frequency, the shorter each frame is, and then the smaller the transmittance difference. On the contrary, as frame rate decreases, each frame is long enough to allow the LC directors to complete the transition. Further decreasing frame rate causes flickering to saturate, as Figure 3e depicts.

3.2. *Dielectric anisotropy effect*

Next, we chose five LC mixtures (four positive and one negative) to investigate how the dielectric anisotropy influences the FEE of an FFS cell. The measured results are shown in Figure 4. As $\Delta\varepsilon$ decreases from 10 to 3.5, the dynamic transmittance variation gets smaller, resulting in a suppressed image flicker. Meanwhile, when an LC mixture with negative $\Delta\varepsilon$ is employed (Figure 4e), the transmittance changes more smoothly, which in turn leads to a negligible image flicker. These results are consistent with previous reports, where the n-FFS mode exhibits unnoticeable image flickering.[7,8]

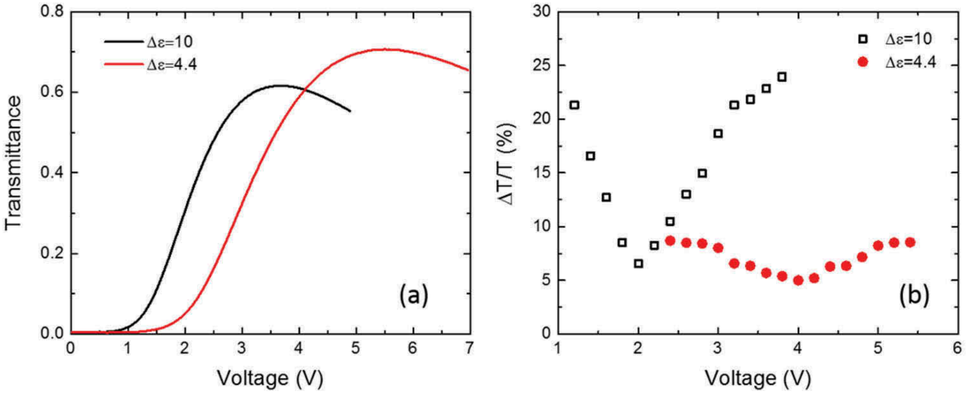

Figure 2. Measured (a) VT curves and (b) image flicker of two LC mixtures with $\Delta\varepsilon = 10$ and $\Delta\varepsilon = 4.4$ (Table 1). FFS cell parameters: electrode width = 3 μm, electrode gap = 4 μm and cell gap = 3.5 μm. λ = 633 nm.

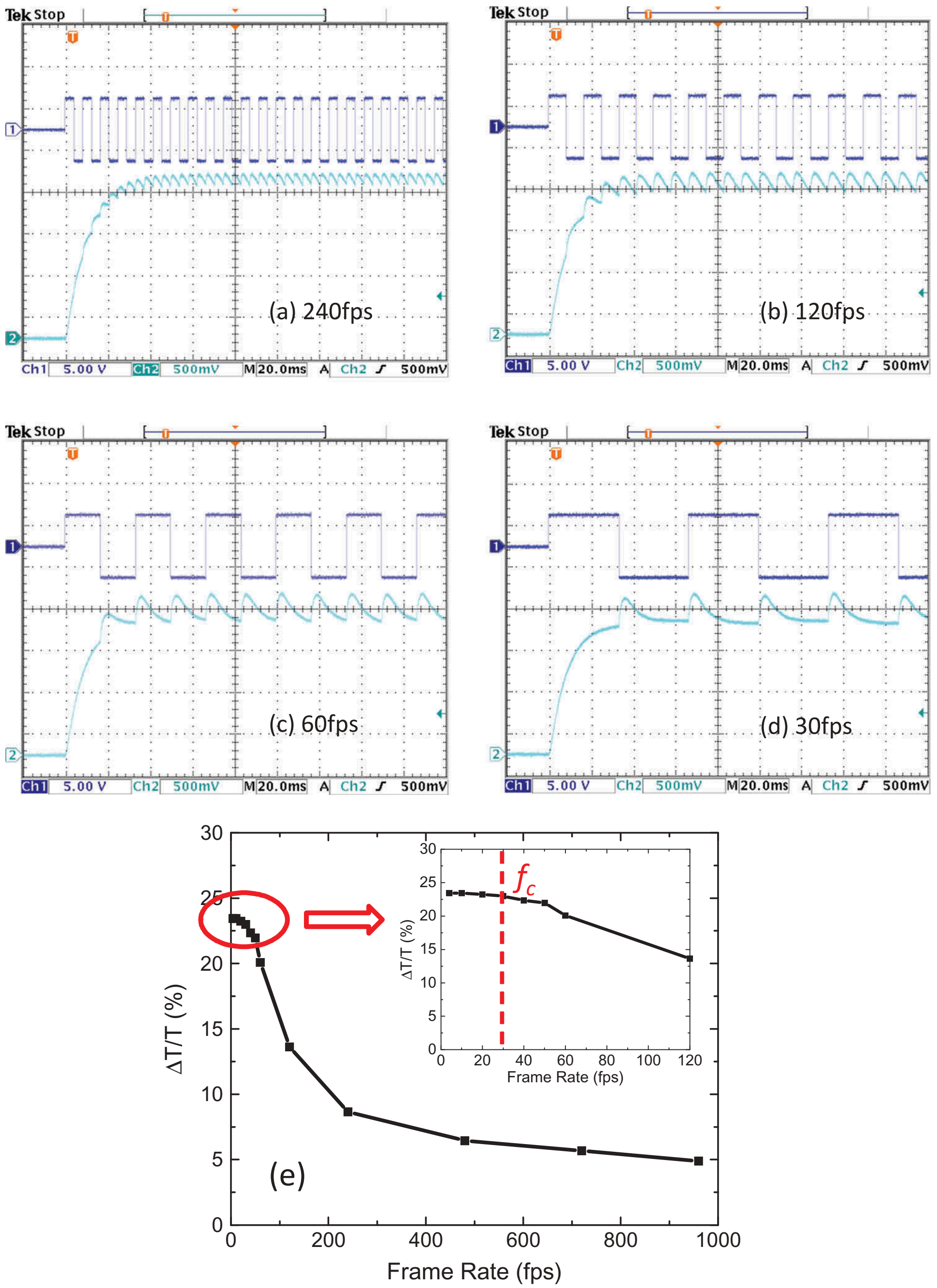

Figure 3. (a–d) Dynamic transmittance at different frame rates. (e) Relation between image flicker and frame rate. LC: MLC-6686 with $\Delta\varepsilon = 10$ and $\lambda = 633$ nm.

Figure 5 summarises the *F*-value for each LC mixture. Clearly, the image flicker keeps decreasing from 20% to 6% when $\Delta\varepsilon$ decreases from 10 to 3.5. More amazingly, the *F*-value drops to 3.5% with $\Delta\varepsilon = -4.4$. From Equation (1), the flexoelectric polarisation is governed by two factors: e_{11} and e_{33}, and spatial derivatives of the LC directors, $\vec{n}$, or namely the deformations of LC molecules. For a positive LC, larger $\Delta\varepsilon$ means larger dipole moment and larger shape polarity, thus a larger flexoelectric coefficient is expected. In addition, a large tilt deformation will be induced if the LC has a large $\Delta\varepsilon$, which in turn amplifies the flexoelectric polarisation.[6] Therefore, the image flicker increases with increasing $\Delta\varepsilon$. For a negative $\Delta\varepsilon$ material, the LC molecules are more uniformly distributed, [7,8] leading to a much smaller flickering.

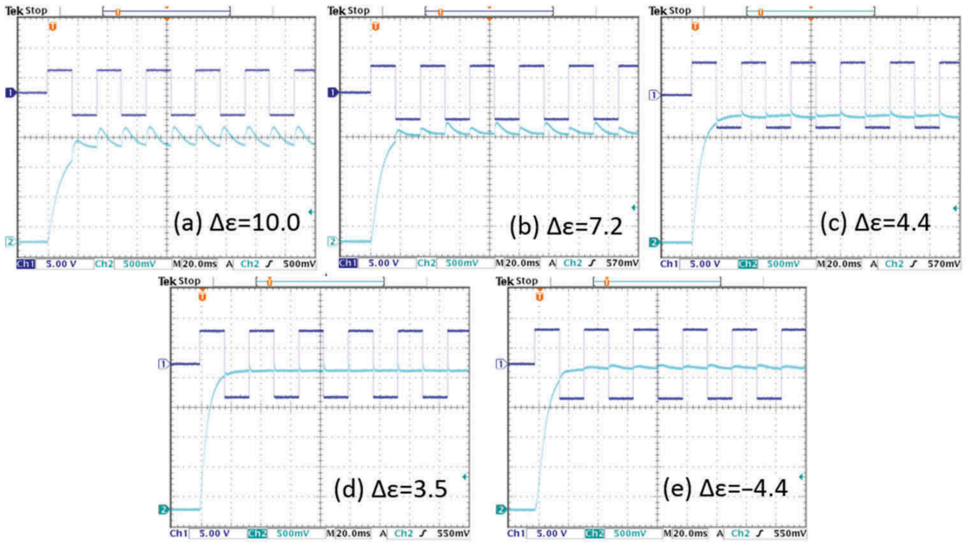

Figure 4. (a–e) Dynamic transmittance for LC mixtures with different dielectric anisotropies. Frame rate: 60 fps.

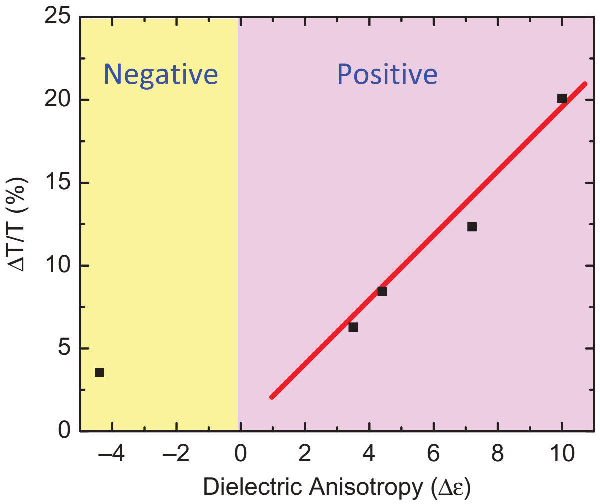

Figure 5. Relation between image flicker and dielectric anisotropy. Frame rate: 60 fps.

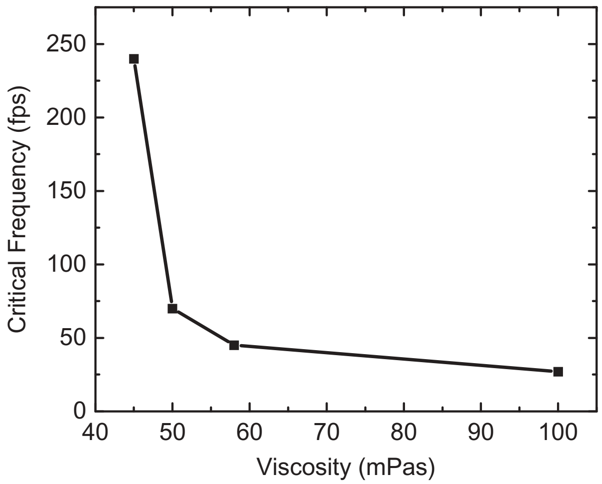

Figure 6. Measured critical frame rate versus LC rotational viscosity.

3.3. *Viscosity effect*

In Figure 3e, there exists a critical frequency (f_c) below which the image flicker does not change any more. This is because the LC directors have enough time to relax and the resultant transmittance saturates, as Figure 3d shows. Obviously, this critical frequency depends on the speed of LC reorientation. If the LC has a faster response time, a shorter time is needed to complete the transition between different frames. Thus, image flicker will saturate at higher frequency, as depicted in Figure 6. For a low-viscosity LC mixture, say γ_1 = 45 mPa·s, the critical frame rate is as high as 240 fps. It indicates the image flicker would remain the same as long as the frame rate is slower than 240 fps. Meanwhile, low flicker is expected since low viscosity and low dielectric anisotropy are usually correlated.[11]

3.4. *Flicker sensitivity*

Until now, we use the parameter *F* to quantitatively compare the image flicker for different materials at different frame rates. However, we have not yet considered the human eye sensitivity. In reality, we need to figure out at which level the flicker would be detectable by the human eye. This could be characterised by the flicker sensitivity, which is a concept in the psychophysics of vision.[25,26] It is defined as the modulation depth at which an intermittent light stimulus appears to be completely steady to the average human observer when measured at a series of fixed frequencies.

Several parameters affect the ability to detect flicker, such as frame rate, modulation depth, illumination intensity, wavelength (or wavelength range) of the illumination, the position on the retina at which the stimulation occurs, the degree of light or dark adaptation, and the physiological factors such as age and fatigue.[27,28] In our experiment, we invited seven males and three females (age between 25 and 30) as observers. The employed light source is Pocker-Vue CL-5000P with cold cathode tube, driven by DC current in order to eliminate the blinking of backlight. Also, the experiment was conducted under dimmed ambient light. Results are shown in Figure 7. As expected, as the frame rate increases, the threshold modulation depth increases in order to notice flickering. This trend is consistent to previous findings for flicker perception.[24–26]

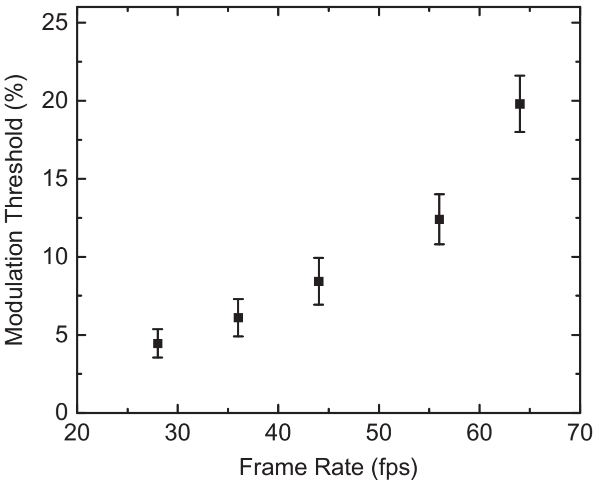

Figure 7. Relation between modulation threshold and frame rate.

4. Discussion

A conventional way to evaluate the performance of an LCD, such as transmittance or operation voltage, is objective, which means no human factor is involved. But detecting image flicker could be quite subjective; it depends on the human eye's perception. Therefore, the absolute value $F = \Delta T/T$ alone is difficult to quantify image flicker. In this sense, image flicker is analogous to the colour shift of a display device. As long as $\Delta u'v' < 0.02$, colour shift is unnoticeable to the human eye. Thus, it is not necessary to spend a great deal of effort to further reduce the $\Delta u'v'$ value.[29] Similarly, the flicker sensitivity line representing the threshold (heavy green line, Figure 8) is more meaningful in reality. Above this line, the flicker is noticeable, leading to a degraded image quality and eye strain. Below this line, the flicker is unnoticeable.

This flicker sensitivity line serves as an important guideline for optimising LC materials and display devices. For example, if we want to drive an LCD at 60 fps, then we should keep $\Delta\varepsilon \le 7.2$. On the other hand, if an LC with $\Delta\varepsilon = 4.4$ is employed, the driving frequency should be higher than 40 fps in order to suppress flicker to invisible level. In Figure 8, the yellow region indicates image flickering is unnoticeable to the human eye.

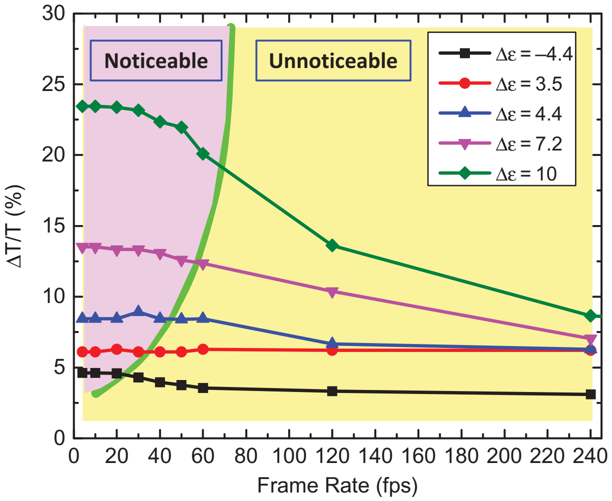

Figure 8. Frame rate-dependent image flicker for LC mixtures with different dielectric anisotropies. The heavy green line represents the flicker sensitivity boundary.

As discussed above, the flicker detection is governed by several factors. Thus, in real applications, the flicker sensitivity line obtained here could vary slightly for different purposes and different device configurations. For example, the strength and spectrum of the backlight, the electrode structure of the FFS cell and the driving frequency of TFT will play important roles in flicker perception. In addition, the expected consumer groups should also be taken into consideration since the physiological factors such as age and fatigue will take effect as well. With so many variables, however, our flicker sensitivity line still serves as an important guideline for further optimisations. Meanwhile, low $\Delta\varepsilon$ LC mixtures exhibit smaller image flicker; this tendency should be consistent in spite of the device configurations.

5. Conclusion

We have analysed the FEE in FFS cell thoroughly, and the image flickers are measured and compared with different materials at different frequencies. By comparison, we found that LC mixtures with low but positive $\Delta\varepsilon$ help to suppress the FEE, and image flicker with $\Delta\varepsilon \leq 7.2$ LCs is unnoticeable at 60 fps. Besides, flicker sensitivity line for FFS cell is obtained, which offers the guidance for optimising LC materials and display devices. This discovery will have a huge impact on mobile displays, especially in the elimination of image flicker using a positive $\Delta\varepsilon$ LC mixture.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The authors are indebted to AU Optronics (Taiwan) and Office of Naval Research for the partial financial supports [contract no. N00014-13-1-0096].

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