Photoelectric Properties and Drive Characteristics of GH Liquid-Crystal Cells in Various Alignment Modes

Shuichi Sato*, Tetsuya Chikama, and Mikio Ohuchi

Department of Electronic Engineering, Tokyo Denki University, 5 Senju-Asahi-cho, Adachi-ku, Tokyo 120-8551, Japan
*s.sato@mail.dendai.ac.jp

Photoelectric properties and drive characteristics of guest-host (GH)-type liquid crystal cells with yellow, magenta, cyan, green, and gray colors using 4-cyano-4'-pentylbiphenyl (5CB) and three diazo-based dichroic dyes were systematically investigated in different driving modes. The dichroic dyes have structures similar to 5CB; therefore, they uniformly mixed and dispersed into the liquid crystal matrix. The green and gray colors were obtained by mixing appropriate ratios of two or more dyes. Impedance of the GH cells decreased upon the incorporation of the dyes into 5CB. However, the photoelectric properties and drive characteristics of the liquid crystal cells were not altered after the inclusion of the dye. In particular, the alignment of the molecules strongly depended on the cell structure. The GH cells in twisted nematic mode exhibited a low driving voltage of approximately 1.5 V.

Keywords: Liquid crystal, Guest-host cell, Dichroic dyes, Twisted nematic, In-plane-switching

1. Introduction

Optical devices such as televisions and cellphones play an important role in broadcast and information technology industries. Various technologies such as liquid crystals [1,2], plasma [3], inorganic electroluminescence [4], organic electroluminescence [5,6] have been developed for the fabrication of optical displays. Conventionally, in a liquid crystal display (LCD), two polarizers are placed vertically to block the light. By applying a voltage, the transmission of light is controlled with a liquid crystal layer located between the polarizers. The color in LCD is realized by passing the light through a color filter that is located outside the polarizer. Typically, a glass colored with an array of red, green, and blue pigments acts as the color filter. Therefore, the liquid crystal layer is not involved in colorization.

Guest-host (GH)-type liquid crystals were originally proposed by Hililmeier in 1968 [7]. They are a class of liquid crystals in which the colorization function is achieved by the addition of a dye (the guest) into a liquid crystal (the host). As the transmittance in the liquid crystal device is controlled by the movement of liquid crystal molecules, the alignment direction can be changed by applying an electric field. As the dyes are incorporated in the liquid crystal, they follow the movement of liquid crystals. As the colorization function is integrated into the liquid crystal, they can be considered to be an energy saving display technology and can be applied as dimming glasses for offices. Recently, there has been a strong interest in the study of this type of LCD technology [8].

As the GH-type liquid crystal device is composed of the liquid crystal and the dichroic dye, the compatibility between the host and the guest is essential in determining the driving characteristics of the liquid crystal cell. For the preparation of colors such as green or gray, it is necessary to mix appropriate ratios of the basic yellow, magenta, and cyan dyes. When multiple pigments are mixed, the driving characteristics can alter the electrical characteristics. In particular, gray color is important for applications such as dimming glass. However, there is no
evidence about the characteristics for the mixed GH-type liquid crystal devices reported in the literature.

Various driving modes for liquid crystal devices have been developed. The driving modes include the twisted nematic (TN), In-plane-switching (IPS), and Vertical alignment (VA) modes. In the TN mode, the liquid crystals are aligned with a twist of 90 degrees from the state where the liquid crystal is horizontally placed on the substrate. Upon the application of a voltage, the liquid crystals become vertically aligned. In the IPS mode, the liquid crystals are horizontally aligned, and when the voltage is applied, the orientation changes horizontally in the plane of the comb-shaped electrode. In the VA mode, the liquid crystals are vertically aligned on the substrate, and the molecules are tilted in the presence of an electric field. However, the fundamental operating characteristics of GH-type liquid crystal devices under different driving modes have not been reported to our knowledge.

In this study, the photoelectric properties and driving characteristics of GH-type liquid crystal devices with different colors and driving modes were systematically investigated. A TN-type liquid crystal, 4-cyano-4'-pentylbiphenyl (5CB) with a relatively simple chemical structure was employed as the liquid crystal. Diazo compounds with yellow, magenta, and cyan colors were used as the dichroic dyes. As the molecular structure of the diazo dyes are similar to 5CB, the dyes uniformly mixed and dispersed into the liquid crystal matrix. The operating performances of the yellow, magenta, cyan, green, and gray colored GH liquid crystal devices were investigated. The green and gray color GH liquid crystals were obtained by mixing appropriate ratios of two or more dyes.

2. Experimental
2.1. Sample preparation
The chemical structures for 5CB and the dichroic dyes (G470, G471, and G472) employed in this study are depicted in Figure 1. The 5CB is a TN-type liquid crystal, while the dichroic dyes for yellow, and magenta, and cyan are labeled as G470, G471, and G472, respectively. The 5CB liquid crystal was purchased from Wako Pure Chemical Industries, Ltd., Osaka, Japan, while all the dichroic dyes were obtained from Hayashibara Co., Okayama, Japan. First, a GH-type liquid crystal for each dye was prepared, by mixing 1 wt% of dichroic dye into the liquid crystal, and then, the resulting mixture was heated to 80°C. Subsequently, these solutions were poured into the liquid crystal cell for each driving mode examined in this study. The liquid crystal cell with green color was prepared by mixing equal parts of yellow and cyan dyes while keeping the total dye weight fraction with respect to the final GH mixture at 1 wt%. For the fabrication of the gray cell, yellow, magenta, and cyan dyes were mixed in a ratio of 8:3:9, respectively.

In this study, we examined the driving
characteristics of GH-type liquid crystals in four different driving modes: TN, IPS, VA, and one with no alignment. The cell for the TN mode (1), in which horizontal alignment was twisted to the left by 90° between the upper and lower substrates, was prepared with the rubbing method. The cell for the IPS mode (2) with the horizontal alignment of the liquid crystal was achieved by a rubbing method using a comb electrode with an electrode interval of 10 μm. The cell for the VA mode (3) with vertical alignment of liquid crystals was obtained by the rubbing method. Finally, a cell without any alignment was also fabricated (4). The liquid crystal cells were purchased from E.H.C. Co., Tokyo Japan. Each cell in the liquid crystal had a cell gap of 10 μm, the resistance of the Indium Tin Oxide (ITO)-based transparent electrode was 100 Ω/m², and the total electrode area of the square shaped cell was 100 mm². The GH-type liquid crystal cell for each driving mode was fabricated for each color individually and the cell structures for each drive mode are illustrated in Fig. 2.

2.2. Optical and electrical property analysis

The ultraviolet visible absorption (UV-vis) spectra in the range of 190–800 nm was recorded with a V-670 spectrophotometer (Jasco Co., Tokyo, Japan) at room temperature. The theoretical UV-vis absorption spectra for assigning the interband transitions corresponding to the peaks in the absorption spectra was calculated using the molecular mechanics simulator Gaussian 09W (Gaussian Inc., Wallingford, USA), based on the MOPAC (PM3 parameter).

The impedance at each frequency was measured with a chemical impedance analyzer (Model No. IM 3590, Hioki EE Co., Nagano, Japan). The applied voltage was 0.5 V and the frequency ranged between 0.01 Hz to 200 kHz. The measurement was performed in a four-probe electrode arrangement. The driving characteristics of the GH-type liquid crystal cell was determined by measuring the difference in the voltage of a photodiode, following a burst waveform input to the cell using a function generator (Model No. AFG3021B, Tektronix, Inc., Beaverton, Oregon, USA). The voltage was measured with an oscilloscope (Model No. TDS2022B Tektronix, Inc., Beaverton, Oregon, USA). The change in the voltage is a measure of the light transmitted through the liquid crystal cell.

3. Results and discussion

3.1. Optical properties of the guest-host-type liquid crystal cell

Figure 2 displays the photographs of the GH-type liquid crystal cells for the different drive modes, TN mode, IPS mode, VA mode, and without alignment. The yellow, magenta, cyan, green, and gray colors were observed in all the driving modes, though the degree of coloration achieved in the liquid crystal cell depended on the driving mode. A dense coloration was observed
in TN mode and IPS mode, where the substrate was subjected to a horizontal alignment treatment. A faint color nearing transparency was observed in the VA mode, although the concentration of the dye in the liquid crystal remained similar to that in the other drive modes. Finally, the liquid crystal cell without alignment, a faint color was observed in the central part where the ITO substrate was deposited, and the other parts of the cell displayed a dense coloration with an intensity similar to that of the TN and IPS modes. From these observations, we conclude that the cells in which the dyes are oriented horizontally with the respect to the long axis display the deepest color due to higher light absorption, while vertical orientation results in poor coloration. In the case of the GH cells without alignment, a faint color was observed, as liquid crystals are arranged relatively vertically. For this drive mode, there was a near vertical arrangement of the liquid crystals when ITO was present, while a near horizontal arrangement on the glass substrate, where ITO was not deposited.

The absorption spectra were recorded to investigate the coloration properties for the different drive modes. The UV-vis spectra of the liquid crystal cell in the different drive modes are depicted in Fig. 3. The spectra measured the optical response from the entire cell consisting of a glass substrate, ITO electrode, 5CB (liquid crystal), and dichroic dyes. In all liquid crystal cells, a remarkably strong peak was observed in the region of 200–400 nm. Peaks centered around 450 nm, 550 nm, and 650 nm were observed in the GH cells with yellow, magenta, and cyan dye, respectively. These absorption peaks correspond to the complementary color that was detected for each dye. Absorption peaks associated with the yellow and cyan dyes were noted in the two-dye based green GH cell. Absorption bands associated with the yellow, magenta, and cyan dyes were observed in the three-dye based gray GH cell. The overall mixing of the absorption bands of the three dyes.
resulted in one broad band in the range of 400–800 nm. Among the four drive modes, the largest absorbance band was observed for the TN and IPS modes, where the horizontal alignment treatment resulted in a dense color. In contrast, absorption bands with low absorbance values was observed in VA mode and without alignment treatment whose color was faint. For the cells with the TN and VA drive modes as well as the cell without alignment, an interference peak associated with the two ITO films (deposited on the upper and lower substrates) was observed in the entire wavelength range. On the other hand, the IPS mode GH cell displayed the strongest peak in the visible region (among all driving modes) with no interference peaks. Thus, the alignment of liquid crystal and the dye play an important role in determining the optical properties of the GH cell.

With the help of theoretical calculations, the electronic transitions in the different molecules were analyzed in order to assign the absorption peaks observed in Fig. 3. The highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of 5CB, G470 (yellow), G471 (magenta), and G472 (cyan) are shown in Fig. 4. The HOMO-LUMO transition indicates an electron-density transfer between the two states. It is important to note that the charges in the HOMO and LUMO of 5CB were located on the biphenyl component sites. The photo adsorptions of the 5CB depends on the charge transfer in the biphenyl site due to the π-π* transitions of the phenyl group. On the other hand, with respect to each dye, HOMO and LUMO were located in the naphthalene site, which was located at the center of the molecule. The photo absorptions of the dyes depend on the charge transfer in the naphthalene site because of the phenyl group π-π* transitions, as well as 5CB.

Figure 5 displays the calculated photo absorption spectra of the liquid crystal and the dichroic dyes. For all materials, a remarkable broad peak caused by organic materials was observed in the range of 200–300 nm. Additionally, some peaks for the HOMO-LUMO transition of the 5CB and dyes were observed above 300 nm. The order of absorption wavelength was Cyan > Magenta ≥ Yellow > 5 CB. The energies of HOMO and LUMO levels for the liquid crystal and the dichroic dyes are as

![Figure 4](image-url)

**Fig. 4.** HOMO and LUMO compositions of the frontier molecular orbital for the molecules 5CB, G470, G471, and G472, respectively.
follows:

5CB: $-9.27$ eV (HOMO), $-0.79$ eV (LUMO).

G470: $-8.43$ eV (HOMO), $-1.43$ eV (LUMO).

G471: $-8.62$ eV (HOMO), $-1.63$ eV (LUMO).

G472: $-8.45$ eV (HOMO), $-1.84$ eV (LUMO).

The energy between HOMO and LUMO, which is a measure of the energy of transition, decreased with increase in the molecular size. Therefore, it is estimated that the order of the low energy transition was Cyan $>$ Magenta $\geq$ Yellow $>$ 5CB. This order was in good agreement with the experimentally observed absorption spectra (see Fig. 3). These results also indicate that the absorption wavelength can be tuned by controlling the molecular size and the position of the naphthalene component. These measurements clearly reveal that the dichroic dyes with similar chemical structure can be mixed into the liquid crystal without phase separation.

3.2. Electrical properties of guest-host-type liquid crystal cell

The drive characteristics and electrical properties of the GH cells in the different drive modes were systematically investigated. The photographs of the GH cells when voltage was applied are presented in Fig. 6. As evident in Fig. 6 (a), a different optical response in the ITO electrode region of the TN mode GH cell was observed when the voltage was applied. It is likely that the liquid crystal upon the application of a voltage changes into a vertical alignment because the appearance in the center part was almost similar to that observed in the VA mode. The drive characteristics of the GH cells in each driving mode at 100 Hz and the input voltage at which the appearance of the cell changed are tabulated in Table 1. All the GH cells in the TN mode drove at around 1.4 V. However, the GH cells in the IPS mode could not drive until 4.5 V due to a change in the cell structure. In the case of the IPS mode, the ITO electrodes are present on only one of the sides unlike in the TN mode GH cells. As the electric field in the liquid crystal becomes low with the electrode interval in the IPS cell, a higher voltage was necessary to drive these cells. On the other hand, in the case of the VA mode and the GH cells without alignment, wherein the liquid crystal molecules are already aligned vertically, the liquid crystals did not drive when the voltage was applied. In the case of a positive-type liquid crystal such as 5CB, the molecules are aligned along the direction of the applied voltage [9]. Therefore, the cells in the case of the VA mode and those without alignment did not drive, as the liquid crystals were already aligned along the direction...
of the applied voltage.

Next, the drive frequency was examined based on the drive voltage at 100 Hz, as displayed in Table 1. The drive frequencies at which the visual appearance of the cell started to change are tabulated in Table 1. The applied input voltage for the TN mode was 2 V, while a voltage of 6 V was applied for the IPS mode. These voltages are slightly higher than the voltage at which the cell began to drive. The cells in the TN mode were able to switch between the horizontal state and the vertical state at a frequency rate between ~10 Hz\(^{-1}\) to 100 kHz. The driving frequency range in the TN mode was almost constant, even in the case of multiple dye cells such as green and gray. However, the IPS mode cells where the alignment direction switched within the same plane drove for a wider frequency range (several Hz to 1 MHz). We believe that the high input voltage or cell structure determine the driving characteristics.

The impedances of all the GH cells in this study were also analyzed as the driving characteristics are strongly correlated with the electrical properties of the cell. The impedance \(Z (\Omega)\), as a function of the phase difference \(\theta (\degree)\), at each frequency, for the GH cells with the TN mode, IPS mode, VA mode and without alignment are presented in Figures 7 (a)–(d) respectively. To clarify the effect of the dye, the data of the cell without dye (only 5CB) was also measured.

From Fig. 7 (a), it is clear that \(Z\) in the TN mode cells decreased with increasing frequency for all colors. The tendency of the capacitor whose \(\theta\) was \(-90\degree\) was mainly observed in the region below 1 Hz and above 10 kHz. In the plateau region (1 Hz–1 kHz), a resistive component whose \(\theta\) was 0\degree\) was observed. In the region where the capacitor component was dominant, \(Z\) of each color cell was noted to have the same value. However, \(Z\) changed in the plateau region, and the order of \(Z\) was no dye > gray >= green > magenta > yellow > cyan cells. Although

| Alignment mode          | Color  | Driving voltage (V) (Frequency:100 Hz) | Driving frequency (Hz) |
|-------------------------|--------|--------------------------------------|------------------------|
| Twisted nematic (TN)    | Yellow | 1.5±0.1                              | 4–90k\(^{a}\)           |
|                         | Magenta | 1.4±0.1                             | 5–100k\(^{a}\)          |
|                         | Cyan    | 1.3±0.1                              | 8–100k\(^{a}\)          |
|                         | Green   | 1.3±0.1                              | 5–100k\(^{a}\)          |
|                         | Gray    | 1.4±0.1                              | 3–90k\(^{a}\)           |
| In-plane-switching (IPS)| Yellow | 5.0±0.1                              | 4–1M\(^{b}\)            |
|                         | Magenta | 4.6±0.1                              | 4–1M\(^{b}\)            |
|                         | Cyan    | 4.5±0.1                              | 4–1M\(^{b}\)            |
|                         | Green   | 4.4±0.1                              | 5–1M\(^{b}\)            |
|                         | Gray    | 4.5±0.1                              | 4–1M\(^{b}\)            |
| Vertical alignment (VA) | Yellow | ND\(^{c}\)                            | ND\(^{c}\)              |
|                         | Magenta | ND\(^{c}\)                           | ND\(^{c}\)              |
|                         | Cyan    | ND\(^{c}\)                            | ND\(^{c}\)              |
|                         | Green   | ND\(^{c}\)                            | ND\(^{c}\)              |
|                         | Gray    | ND\(^{c}\)                            | ND\(^{c}\)              |
| Without alignment       | Yellow | ND\(^{c}\)                            | ND\(^{c}\)              |
|                         | Magenta | ND\(^{c}\)                           | ND\(^{c}\)              |
|                         | Cyan    | ND\(^{c}\)                            | ND\(^{c}\)              |
|                         | Green   | ND\(^{c}\)                            | ND\(^{c}\)              |
|                         | Gray    | ND\(^{c}\)                            | ND\(^{c}\)              |

\(^{a}\) Input voltage:2.0 V
\(^{b}\) Input voltage:6.0 V
\(^{c}\) Not determined
Z remarkably decreased with the addition of the dye. Z was not dependent on the type of dye. The behavior in the plateau region was in good agreement with the drive frequency region of the GH cells in the TN mode.

The impedance of the IPS mode cells exhibited a similar trend to that of the TN mode; however, the value of Z in the IPS mode was greater than that observed in the TN mode for all color cells [see Fig. 7(b)]. With the addition of the dye, Z remarkably decreased in the plateau region, and the frequency dependence of the electrical property in the IPS mode was nearly identical to that in the TN mode. Consequently, the drive frequency range expansion in the IPS mode is due to the high input voltage, as shown in Table 1.

As evident from Figs. 7(c) and 7(d), Z decreases with increasing frequency in the cells in which the liquid crystal was already aligned vertically, i.e. the VA mode and ones without alignment. However, through all color cells, the plateau region was wider than that observed for the TN and IPS mode cells, where the liquid crystals were horizontally aligned. Since the liquid crystal molecules were already aligned along the direction of the applied voltage, there was no movement of the liquid crystal, resulting in a low resistance. Owing to the random arrangement of liquid crystals, Z in the cells without alignment varied widely in each color cell. These results indicate that the alignment direction was strongly dependent on the electrical properties, even if the materials were the same.

Based on the impedance of all GH cells, the equivalent circuit analysis was performed on the cells in the TN and IPS modes, the cells in which the drive was observed in this study. Although the equivalent circuits of the TN and IPS modes have been reported in previous studies, it has not been accurately analyzed [10]. In this study, an equivalent circuit was analyzed by comparing the
impedance characteristics. From the result, it is possible to discuss which components (the alignment direction or cell structure) mainly affect the electrical property. Figure 8 shows a Cole–Cole plot for the TN mode cell, which is a vector trajectory representing the real part resistance $R$ (Ω) on the X axis and the imaginary part resistance $X$ (Ω) on the Y axis. A figure combining a semicircle and a straight line was observed. In the case of a general liquid crystal cell, the equivalent circuit is represented as a parallel circuit of a capacitor and a resistor as illustrated in Figure 9(a) [11]. When this circuit is represented by a vector locus, only a semicircle is drawn. However, the Cole–Cole plot in this study contained a semicircle for the parallel circuit of a capacitor and a resistor, and a straight line for the capacitor component. Therefore, this equivalent circuit can be represented as the model [see Figure 9(b)] where the other capacitor $C_2$ in addition to the parallel circuit of the capacitor $C_1$ and resistor $R_1$ is connected to the circuit. $Z$ is represented by the following equation:

$$Z = \frac{B_2}{1 + \omega^2 \frac{B_2^2}{R_1^2}} - j \left(\frac{\omega C_1 R_1^2}{1 + \omega^2 C_1 R_1^2} + \frac{1}{\omega C_1} \right)$$

(1)

$R_1$ can be measured from the intersection of the semicircle and the straight line and $X$ can be calculated from the real part of the resistance ($X=R_1/2$). Next, the frequency $\omega_1$ at which $X$ shows a maximum can be substituted in eq. (1) to give:

$$\frac{R_1}{2} = \frac{B_2}{1 + \omega_1^2 C_2^2 R_1^2} \quad \Rightarrow \quad C_1 = \frac{1}{\omega_1 R_1^2}$$

(2)

from which $C_1$ can be obtained. $C_2$ can be calculated with the following eq. (3) from the

$$C_2 = \frac{B_2}{1 + \omega_1^2 C_2^2 R_1^2}$$

Table 2. Equivalent circuit parameters of the different GH-type liquid crystal cell investigated in this study.

| Alignment mode          | Color       | $R_1$ (kΩ) | $C_1 \times 10^{10}$ (F) | $C_2 \times 10^5$ (F) |
|-------------------------|-------------|------------|--------------------------|-----------------------|
| Twisted nematic (TN)    | Yellow      | 370 ± 10   | 5.5 ± 0.1                | 38 ± 1                |
|                         | Magenta     | 500 ± 10   | 6.2 ± 0.1                | 6.7 ± 0.1             |
|                         | Cyan        | 310 ± 10   | 6.2 ± 0.1                | 21 ± 0.1              |
|                         | Green       | 650 ± 10   | 5.6 ± 0.1                | 15 ± 1                |
|                         | Gray        | 580 ± 10   | 6.4 ± 0.1                | 5.0 ± 0.1             |
|                         | No dye      | 1470 ± 10  | 6.4 ± 0.1                | 4.7 ± 0.1             |
| In-plane-switching (IPS)| Yellow      | 1180 ± 10  | 5.2 ± 0.1                | 1.8 ± 0.1             |
|                         | Magenta     | 560 ± 10   | 7.2 ± 0.1                | 5.7 ± 0.1             |
|                         | Cyan        | 780 ± 10   | 4.4 ± 0.1                | 4.9 ± 0.1             |
|                         | Green       | 610 ± 10   | 5.1 ± 0.1                | 5.9 ± 0.1             |
|                         | Gray        | 1090 ± 10  | 5.3 ± 0.1                | 2.2 ± 0.1             |
|                         | No dye      | 3040 ± 10  | 5.6 ± 0.1                | 8.4 ± 0.1             |
imaginary part.

\[ X = \frac{R_1}{2} = \frac{R_1}{1 + \omega^2 C_2 R_1} + \frac{1}{\omega^2 C_2} \]
\[ \therefore C_2 = \frac{R_1}{\frac{1}{2} - \frac{1}{\omega^2 C_2}} \]...(3)

Based on these equations, the parameters of \( R_1 \), \( C_1 \), and \( C_2 \) of the equivalent circuit were calculated. The parameters in the TN and IPS modes through all color cells are summarized in Table 2. \( R_1 \), the resistance of the liquid crystal and dye was in the range of 310–1470 kΩ in the TN mode and in the range 560–3040 kΩ in the IPS mode, with the \( R_1 \) values in the IPS mode being larger than those in the TN mode. Additionally, a reduction in the resistance was observed after the doping of the dye, similar to another report in the literature [12]. On the other hand, \( C_1 \) due to the capacitance of the liquid crystal and the dye showed a value of 5.5–6.4 \( \times 10^{-10} \) F in the TN mode and 4.4–7.2 \( \times 10^{-10} \) F in the IPS mode, with only a negligible difference between the two modes. Finally, the capacitance \( C_2 \) between the liquid crystal layer and each electrode exhibited a value of 4.7–38 \( \times 10^{-5} \) F in the TN mode and 1.8–5.9 \( \times 10^{-10} \) F in the IPS mode, with the values in the TN mode being higher than those in the IPS mode. This difference arises as a result of the difference in the area of the electrode and the alignment film [see Fig. 10]. In the case of the TN mode (Fig. 10 (a)), both the upper and lower sides of the liquid crystal layer were in contact with the ITO electrodes. However, there were two ITO electrodes on one side of the liquid crystal layer in the IPS mode [refer to Fig. 10 (b)]. The value of \( C_2 \) decreased because the electrode area in the IPS mode was much smaller than that in the case of the TN mode.

Finally, the relationship between the electrical properties and the driving characteristics of the GH cells in TN and IPS mode was investigated systematically. A burst sinusoidal wave at a 100 Hz interval and a duration of 400 ms was input to each GH cell, and the change of the photodiode voltage was monitored as the diode voltage is directly correlated to the light transmitted through the cell. The input voltage in these experiments was set to 8.0 V for the IPS mode and 5.0 V for

Fig. 10. Equivalent circuit images for (a) TN mode and (b) IPS mode alignment GH-type liquid crystal cells.

Fig. 11. Measured response time for (a) TN mode and (b) IPS mode alignment GH-type liquid crystal cells.
the TN mode. The applied voltage was higher in order to make it easy for the detection of small changes in the transmission of light. The photodiode output waveform for the input burst waveform of the TN mode and IPS mode are displayed in Fig. 11(a) and (b), respectively. As the electrical properties of the different colored cells were similar, only the data of the gray cells with high opacity is illustrated in Fig. 11. Since the liquid crystal is colorless, it was impossible to detect any changes in the photodiode voltage. Therefore, the results from the experiments are restricted to those from the GH-type cells where the dye has been incorporated. In the case of the TN mode in Fig. 11(a), the light transmittance remarkably increased for 50 ms with the input voltage, then decreased for 50 ms and was stable for 200 ms. When the cell was switched off, the transmittance gradually decreased in two steps. This two-step decrease in the light transmission can be attributed to a two-step change when switching between the horizontal and vertical orientation. In the case of the IPS mode, the transmittance increased sharply at 50 ms with the input voltage; subsequently the increase occurred at a slower rate and gradually reached a steady state as evident from Fig. 11(b). When the IPS mode cell was switched off, a sharp decrease in the transmittance was observed for 50 ms, which gradually converged to a constant value. The higher voltage was necessary for driving the cells in the IPS mode as the liquid crystal moves while keeping the horizontal orientation for the in-plane switching. Therefore, the change of the transmittance in the IPS mode was stable in comparison to the TN mode. The driving mode of the GH cells also strongly depend on the responsiveness.

4. Conclusion

In summary, the photoelectric properties and drive characteristics of the GH-type liquid crystal devices with yellow, magenta, cyan, green, and gray colors using 5CB and a diazo-based dichroic dyes were systematically investigated for cells in the TN mode, IPS mode, VA mode, and without any alignment. Although the impedance of the GH cells decreased when the dyes were introduced as a guest into the liquid crystal, the overall driving characteristic remained similar. The alignment of the molecules was strongly correlated with the drive mode and the structure of the cell. The electrical properties also affected the driving characteristics of the GH cells. The GH cells in the TN mode exhibited the lowest driving voltage of approximately 1.5 V in this study.

Acknowledgement

This research was partially supported by a Grant-in-aid for Young Scientists B (26870611) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References

1. G. H. Heilmeier, *IEEE T. Electron Dev.*, 23 (1976) 780.
2. G. H. Heilmeier, L. A. Zanoni, and L. A. Barton, *Appl. Phys. Lett.*, 13 (1968) 46.
3. H. G. Slottow, *IEEE T. Electron Dev.*, 23 (1976) 760.
4. E. W. Chase, R. T. Hepplewhite, D. C. Krupka, and D. Kahng, *J. Appl. Phys.*, 40 (1969) 2512.
5. G. Gu, V. Bulović, P. E. Burrows, S. R. Forrest, and M. E. Thompson, *Appl. Phys. Lett.*, 68 (1996) 2606.
6. C. W. Tang and S. A. VanSlyke, *Appl. Phys. Lett.*, 51 (1987) 913.
7. G. H. Heilmeier and L. A. Zanoni, *Appl. Phys. Lett.*, 13 (1968) 91.
8. J.-W. Huh, S.-M. Ji, J. Heo, B.-H. Yu, and T.-H. Yoon, *J. Disp. Technol.*, 12 (2016) 779.
9. S.-T. Wu, C. Wu, M. Warenghem, and M. Ismaili, *Opt. Eng.*, 32 (1993) 1775.
10. M. Oh-e, Y. Umeda, M. Ohta, S. Aratani, and K. Kondo, *Jpn. J. Appl. Phys.*, 36 (1997) L1025.
11. B. J. Lechner, F. J. Marlowe, E. O. Nester, and J. Tults, *Proc. IEEE*, 59 (1971) 1566.
12. P. Kumar, Neeraj, S.-W. Kang, S. H. Lee, and K. K. Raina, *Thin Solid Films*, 520 (2011) 457.