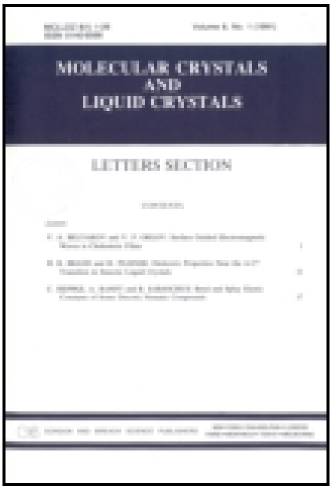

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Electro-Optical Properties of LCD Doped with Nanoparticles and with Optical Compensators: Ways for Fast Response

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This paper consists of two Parts. In the Part 1, we report the experimental results and considerations of the reduction of operation voltage and response time of narrow-gap TN(NTN)-LCDs embedded with the nanoparticles of hydrophobic Aerosil silica. While, in the Part 2, we give a report of the reduction of response time, especially τ_{off} for the decay process of optically compensated tunable birefringence (OCTB)-mode LCD.

Keywords LCD; threshold voltage; nanoparticle; response time; Kobayashi temperature; OCTB-LCD; optical compensation

1 Introduction

Nowadays, there exist demands for LCDs that are characterized by their low power consumption, low operation voltage, and fast response speed. For solving these problems, in a previous work, we adopted an approach of the doping of nanoparticles of PγCyD-ZrO_2 into narrow-gap TN (NTN) LCD [1, 2].

In the present report, we report two contents: one is as the Part 1 on the reduction of both the operation voltage and response time of NTN-LCD embedded with the nanoparticles of hydrophobic Aerosil silica R-812 and RY-300, and the other is as the Part 2 on the reduction of response time, especially τ_{off} of an optically compensated tunable birefringence (OCTB) mode-LCD. And we give some physical explanations on these phenomena.

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2 Part 1

Reduction of operation voltage and response time by doping nanoparticles into NTN-LCD

2.1 Experimentals in the Part 1

LCD cells and materials used in this research are as follows:

1) LCD cells

   (A) Narrow-gap TN (NTN) LCD cells, NTN-1 and NTN-2 with the cell gap of d = 3 μm
   (B) ECB cell with d = 20 μm

2) Nematic materials are
   NTN-01(DIC), NTN-02(DIC) for NTN-LCD with a chiral dopant ACH-1(DIC)
3) Nanoparticles

   (A) PγCyD-ZrO_2 (0.075wt%) for NTN-LCD and ECB
   (B) Hydrophobic Aerosil silica R-812 and RY-300 (1wt%) for NTN-LCD

2.2 Experimental results in the Part 1

2.2.1 Reduction of operation voltage of NTN-LCD cell doped with the nanoparticles of hydrophobic Aerosil silica R-812. Figure 2-1 shows the V-T curves of the NTN-2 cells with an NLC, NTN-02. There are four lines such that: except the second line from the most

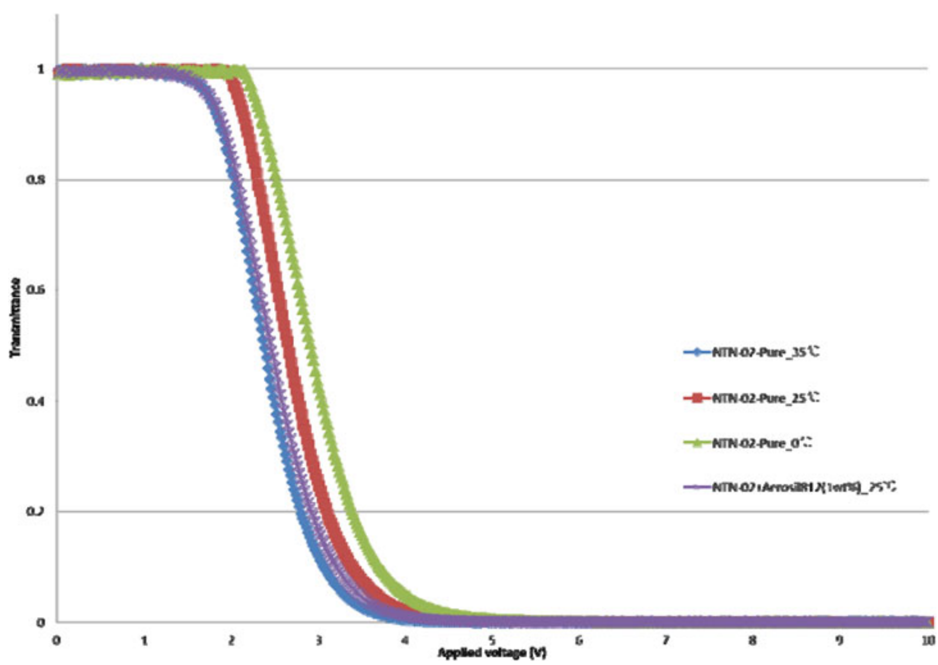

Figure 2-1. V-T curves NTN-cells with NTN-02 without and with hydrophobic nanoparticles silica at 25°C, 35°C, and 0°C.

left one, other all lines are for NTN-02 cells with pure NLC, NTN-02. The second line from the most right one is the V-T curve of an NTN-02 cell with pure NTN-02 at 25°C. The third line from the most right one is for an NTN-02 cell with NLC, NTN-02 embedded with the nanoparticles of hydrophobic Aerosil®812, 1wt% at 25°C. The most left line is for pure NTN-02 at 35°C, and finally the most right line is for the pure NTN-02 at 0°C.

It is recognized that the third line almost exactly corresponds with the fourth line at the threshold voltage and that there occurs a shift of the threshold voltage toward the low voltage side by −7%. From these data it is considered that the existence of nanoparticles may be equivalent with a situation of as if the raising of temperature by 10and this may produce an disordering in the whole region of NLC and this may bring the reduction of order parameter, *S*. They call this temperature Kobayashi temperature. However, at a high operation voltage, say at 3.5V, the value of the shift in NTN-2 cell with nanoparticles is a little bit small. This may be due to the increase of order parameter under the application of a high voltage [3]. The most right line is a reference that demonstrates the effect of lowering temperature down to 0. Actually, the relative reduction of threshold voltage is −7% due to nanoparticles, so that the relative decrease of order parameter may be -14% that is give by the relation such that $\frac{\delta V_{th}}{V_{th}} = \left(\frac{1}{2}\right) \delta S/S$ [4]. In the latter section, more detailed discussion on the relationship between the voltage shift due to nanoparticle doping and the raising of temperature will be given.

2.2.2 The effect of chiral dopant on the pure NLC, NTN-02. Generally, the introduction of a chiral dopant into a TN-LCD cell bring an increase of operation voltage and a decrease of response time for the voltage off process, τ_{off}. The same is true for our NTN-LCD.

The doping of chiral agent for the making of the pitch of 12μm, thus produces the p/d = 4, brings the increase of threshold voltage by +10%. This effect may be interpreted by Eq.(1) such that

$$V_{th}\,(\mathrm{TN}) = \pi \sqrt{K_{11} + \frac{1}{4}\,(K_{33} - K_{22}) + 2K_{22}\,(d/p)}, \quad (1)$$

the final term $2K_{22}\,(d/p)$ contributes to increase the V_{th} [5]. There occurs the similar increase at the higher operation voltage.

2.2.3 Reduction of response time by combining the doping of nanoparticles and chiral dopant. Our objective in this research is to realize a fast electrooptical response of NTN-LCD at a low temperature, say at 0. For this reason, we primarily show the data, which is obtained at 0. Figures 2-2 (a) and (b) demonstrate the reduction of response time for the off and on processes, respectively.

In the Fig. 2-2(a), the top line indicates the data for a NTN-LCD, NTN-2 cell without chiral dopant (p = ∞) and without nanoparticles, the second line is on the NTN-cell with p = ∞ and nanoparticles, there occurs the drop ① of the τ_{off} from 8ms to 6.8ms by −15%(↓), and the third line is on the cell with pitch of 12 μm that downs ② to 6ms (−25% ↓), and the bottom line is on the cell with p = 12 μm and with NPs that makes a total drop ③ from 8ms to 5.5ms(−42%).The simultaneous existence of a chiral dopant and NPs is necessary for the stable operation of our NTN-LCD.

Figure 2-2 shows the data of the on process also at 0. There occurs the so called over driving effect at a high voltage region. Again, doping nanoparticles produces a faster response at a higher voltage region.

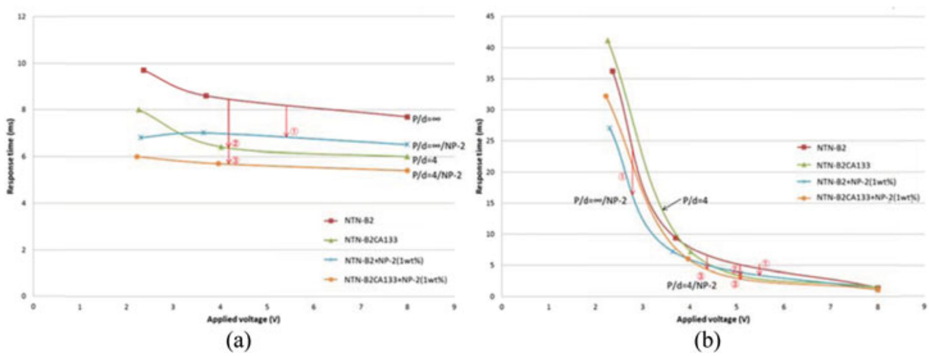

Figure 2-2. Response time vs. operating voltage on the cells with NTN-02, Chiral dopant, and nanoparticles at 0, (a) τ_{off} and (b) τ_{on}, respectively.

The similar trends shown in Fig. 2-2, which is, obtained at 0 also occur in the data obtained at 25°C. However, the obtained values of response time are much shorter at 25°C such that τ_{off} are from 4.2 ms to 2.7 ms (at T = 10%) (−36% ↓) and τ_{on} is around 2 ms at $V_{op} = 6$V.

Similar results of operation voltage and response time were obtained on NTN-cells with the nanoparticles of RY-300.

2.3 Considerations on the reduction of operating voltage and response time in the Part 1

2.3.1 The reduction of V_{th} *by doping nanoparticles.* Doping nanoparticles of hydrophobic Aerosil silica R-812 on the pure NLC, NTN-02 brings the reduction of threshold voltage by −7%; this corresponds to the reduction of the order parameter by −14% and this phenomenon may correspond as if the raising of temperature by 10°C. They call it Kobayashi temperature.

An approximate formulae for V_{th} reads,

$$V_{th} = \pi\sqrt{\frac{K_{eff}}{\varepsilon_0 \Delta\varepsilon}}, \tag{2-1}$$

where, approximately $K_{eff} \propto S^2$ and $\Delta\varepsilon \propto$ S, so that $V_{th} \propto S^{1/2}$ and thus, we get

$$\frac{\delta V_{th}}{V} = \frac{1}{2}\frac{\delta \text{S}}{\text{S}}. \tag{2-2}$$

In our research, we get $\frac{\delta V_{th}}{V_{th}} = -7\%$ (Fig. 2-1), then the order parameter, S may decreases by −14% by the doping of nanoparticle.

There are several approaches for S vs. T such that, the first one is

$$\text{S} = S_0 (1 - T/T_{NI})^{\beta}, \tag{2-3}$$

then we have

$$\frac{\delta S}{S} = \left(\frac{\beta}{1 - T/T_{NI}}\right)\left(\frac{T}{T_{NI}}\right)\left(-\frac{\delta T}{T}\right). \tag{2-4}$$

What we obtained is that $\frac{\delta T}{\mathrm{T}} = 3.7\%$.

Another approach is taken based on Landau-de Gennes free energy expansion [3].

$$F = F_0 + \frac{3}{4}a\left(T - T^*(0)\right)S^2 - \frac{1}{4}BS^3 + \frac{9}{16}CS^4 - \frac{1}{3}DSE^2. \tag{2-5}$$

Order parameter, S is then given as

$$\mathrm{S} = \frac{1}{2}S_{NI} + \left\{\frac{1}{12}S_{NI}^2 - \frac{2a}{9c}(T - T_{NI})\right\}^{1/2}. \tag{2-6}$$

Due to the doping of NPs, the behaviors of $\delta S(\downarrow)$ and $\delta T(\uparrow)$ are effectively such that

$$\delta\mathrm{S}(\downarrow) = -\frac{1}{2}\{F\}^{-1/2}\left(\frac{2a}{9c}\right)\delta T, \tag{2-7}$$

here,

$$\{F\} = \frac{1}{12}S_{NI}^2 - \left(\frac{2a}{9c}\right)(T - T_{NI}), \tag{2-8}$$

so that we have

$$\frac{\delta S}{S} = -\frac{\{F\}^{-1/2}\left(\frac{2a}{9c}\right)T}{S_{NI} + 2\{F\}^{1/2}}\left(\frac{\delta T}{T}\right) \tag{2-9}$$

and

$$\frac{\delta T}{T} = -\frac{2\left[S_{NI} + 2\{F\}^{1/2}\right]}{\{F\}^{-1/2}\left(\frac{2a}{9c}\right)}\left(\frac{\delta V_{th}}{V_{th}}\right), \tag{2-10}$$

where $S_{NI} = \frac{2B}{9C}$ and $T_{NI} - T^*(0) = \frac{B^2}{27ac}$.

These values can be obtained by determining the value of T_{NI} and $T^*(0)$ on the pure and NP doped LCD cells. Determination of the parameters is now underway and results will be published elsewhere.

Regarding the reduction of response time,

τ_{off} is approximately expressed by

$$\tau_{off} = \frac{\gamma_1 d^2}{\pi^2 K_{eff}}. \tag{2-11}$$

So that it's relative decrease reads

$$\frac{\delta\tau_{off}}{\tau_{off}} = \frac{2\delta d}{d} - \frac{\delta\gamma_1}{\gamma_1} + \frac{\delta K_{eff}}{K_{eff}} + \text{surface effect.} \tag{2-12}$$

Referring to our independent experimental measurement on rotational viscosity,γ_1 decrease such that $\frac{\delta\gamma_1}{\gamma_1} = -20\%(\downarrow)$ due to nanoparticles and $\frac{\delta K_{eff}}{K_{eff}} = +20\%(\uparrow)$ due to mainly chiral dopant and plus nanoparticles and an electric field effect. In some other cases, a surface effect may contribute to the change of, τ_{on} and τ_{off}. However, in this system, there occurred

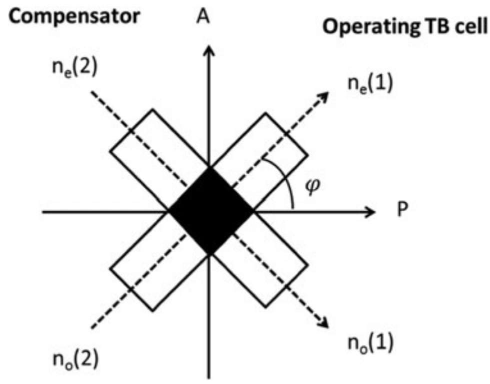

Figure 3-1. Optical configuration of our OCTB-LCD.

a twofold increase of contrast ration that may be attributed to a weak anchoring due to the existence of nanoparticles on the substrate surfaces.

As another example the doping of both the nanoparticles of hydrophobic Aerosil R-812 and chiral dopant ACH-1 into another LCD cell, NTN-1 with fluorinated NLC, brings the reduction of the response time, $\tau_{on} + \tau_{off}$ by -35% at 0°C and -32% at 25°C. Their values are 6.5 ms~ 11.7 ms at 0°C and 6.1 ms~3.8 ms at 25°C depending on the V_{op}.

3 Part 2: OCTB-mode LCD

3.1 Experimentals in the Part 2

In the Part 2, we report the reduction of the response time, especially τ_{off} in our Optically Compensated Tunable Birefringence (OCTB) cell.

Figure 3-1 show the optical arrangement and design of our OCTB cell, where two cells are crossed each other and one is an operating TB cell and the other is an optical compensator. The latter will be three different kinds: the first one is an optically compensating film (+a-plate); the second one is a TB cell, and the third one is an electrically driven TB cell, where all of these optical elements are designed to have their half of phase difference between the ordinary wave and extra-ordinary wave must be $\frac{\pi}{2} - \alpha$, here $\alpha = 0.1 \sim 0.6$.

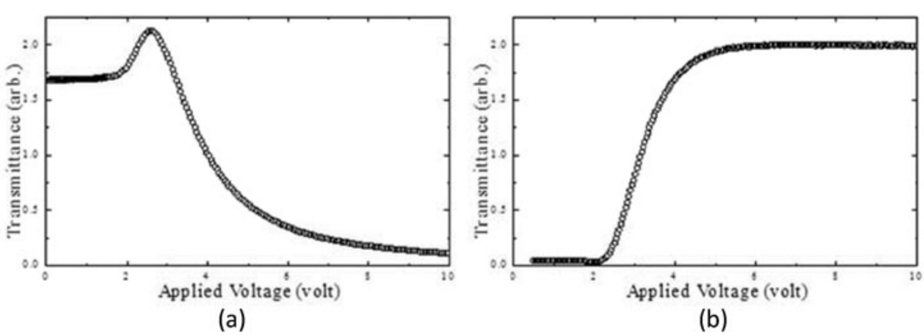

Figure 3-2. V-T curves of TB cells with the half of phase difference is almost $\pi/2$; (a) is the V-T curve of a single TB cell and (b) is that of a crossly stacked TB cell.

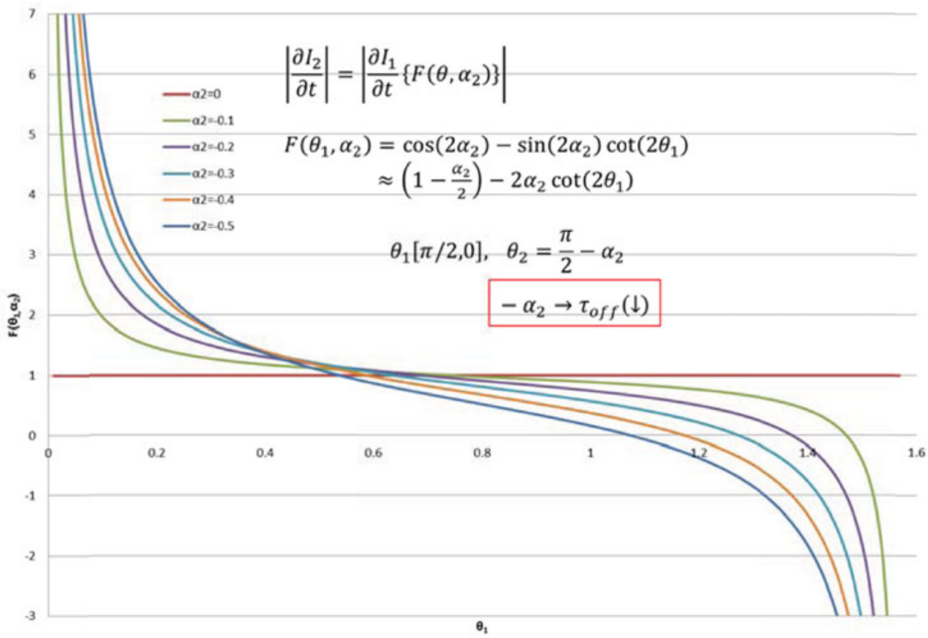

Figure 3-3. Calculation of F.

As a reference, Figure 3-2 show the V-T curves at the quiescent condition($V_{op} = 0$) for (a) a single TB cell and (b) a crossly stacked TB cell.

3.2 Operating principle of OCTB-mode LCD

In a single TB mode cell, the intensity of the optical transmitted light is given as

$$I = I_0 \sin^2(2\varphi)\sin^2\left(\frac{\pi\,\Delta n d}{\lambda}\right), \tag{3-1}$$

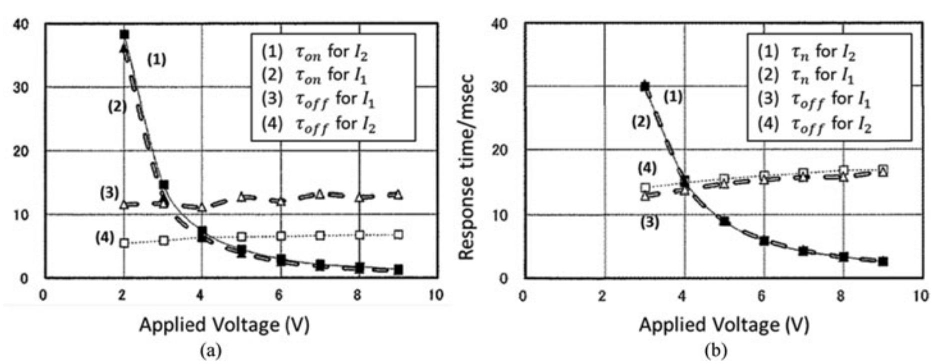

Figure 3-4. Response time of OCTB-cells.

where Δn is the thickness average value of birefringence and this changes from the maximum value to almost zero by increasing applied voltage [6]. If we make a crossly stacked cells as shown in Fig. 3-1, then the intensity of the transmitted light through this system reads

$$I_2 = I_0 \sin^2(\theta_1 - \theta_2), \tag{3-2}$$

where $\theta_i = \frac{\pi d \Delta n(i)}{\lambda}$, $i = 1$ and 2, respectively. At the quiescent condition the I_2 becomes to be zero, dark state and only the θ_1 changes as a function of the applied voltage from it's maximum value to almost zero in the on process; the reversed behavior occurs in the off process.

We have investigated an analytical temporal behavior of Eq(3-2) and we get the following equation:

here,

$$\left|\frac{\partial I_2}{\partial t}\right| = \left|\frac{\partial I_1}{\partial t}\{F(\theta_1, \alpha_2)\}\right|, \tag{3-3}$$

Here, $F(\theta_1, \alpha_2)$ is given as,

$$\begin{aligned} F(\theta_1, \alpha_2) &= \cos(2\alpha_2) - \sin(2\alpha_2)\cot(2\theta_1) \\ &\approx (1 - 2\alpha_2) - 2\alpha \cot(\theta_1), \end{aligned} \tag{3-4}$$

where, the θ_1 is variable and $\partial I_1/\partial t$ is for the single cell, so that in Eq(3-3) the factor $F(\theta_1, \alpha_2)$ determines the ratio of $\left(\frac{\partial I_1}{\partial t}/\frac{\partial I_2}{\partial t}\right)$ and we take $\theta_1 = \frac{\pi}{2} + \alpha_1$ and $\theta_2 = \frac{\pi}{2} + \alpha_2$, further $|\alpha_1| = |\alpha_2|$. However, if we take $\alpha_2 < 0$, then we have the value of $\{F\} > 1$, so that $\left|\frac{\partial I_2}{\partial t}\right| > \left|\frac{\partial I_1}{\partial t}\right|$; this means that the double cell has a faster temporal change than that of the single cell. This phenomenon occurs only for the decaying process.

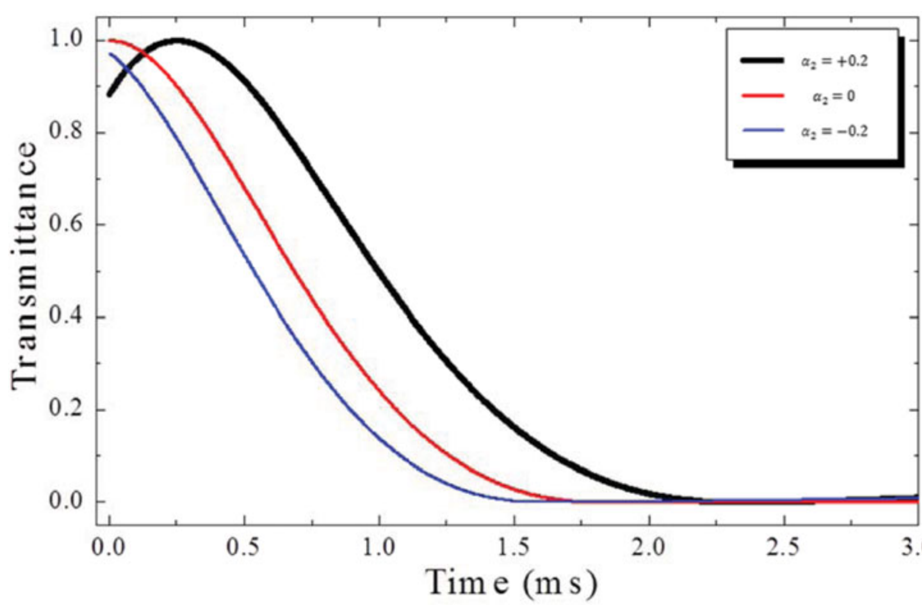

Figure 3-5. OCTB with a dynamic optical compensator.

Figure 3-3 shows the dependence of $\{F(\theta_1, \alpha_2)\}$ on the θ_1 $\{0, \pi/2\}$ as α_2 is a parameter, where $\theta_1 = 0$ corresponds to a vertical alignment of NLC molecules for a high applied voltage. Then, the upper left part of Fig. 3-5 demonstrate the ratio $\{F(\theta_1, \alpha_2)\} = \left|\frac{\partial I_2}{\partial t}\right| / \left|\frac{\partial I_1}{\partial t}\right|$ becomes larger than unity for α_2 <0, say $\alpha_2 = -0.1 \sim -0.6$. This means that our OCTB cell has a shorter response time, τ_{off} than that for a single cell. Only for $\alpha = 0$, we get $\{F(\theta_1, \alpha_2)\} = 1$. Contrary to this, the response time for the on process response time becomes longer than that of the single cell.

3.3 Experimental results in the Part 2

Figure 3-4(a) and (b) demonstrate and compare the values of τ_{on} and τ_{off} in the OCTB cells.

In Fig. 3-4(a), we demonstrate that the τ_{on} for both the double cell and single cell are almost the same; contrary to this τ_{off} for the double cell are shorter almost the half of those in the single cell. This means that our OCTB cell with $\alpha_2 = -0.41$ exhibits almost twice faster response speed than that of the single cell. In the Fig. 3-4(b), we show the results on the OCTB cell with $\alpha_2 = +0.2$, where the response time of τ_{off} in the double cell is longer than that of the single cell by $+10\%$.

Figure 3-5 demonstrates the temporal variations of OCTB with a dynamic compensator. In this case the optical compensator is activated by applying an AC voltage so as to make it's half of phase difference is to be $\theta_2 = \frac{\pi d \Delta n}{\lambda} = \frac{\pi}{2} - \alpha_2$, as Δn decreases with an appropriate increase of the applied voltage. Figure 3-5 shows the decaying process of the dynamic OCTB, where the middle line is for the cell with $\alpha_2 = 0$, and for the right line $\alpha_2 > 0$ $(\alpha = +0.2)$ and further the left line $\alpha_2 < 0(\alpha_2 = -0.2)$.

In this way, the response time is reduced by -25% in the latter case.

3.4 Conclusions in the Part 2

Optically compensated tunable birefringence(OCTB)-mode LCD with the half of optical phase shift of $\frac{\pi}{2} - \alpha_2$, whose $\alpha_2 = 0.1 \sim 0.6$ is proposed and this device is shown to exhibit a fast response, especially in the off process; this gives the reduction of τ_{off} by -50% for a static compensation and -25% reduction of τ_{off} with a dynamic optical compensation.

Acknowledgments

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Appendix A

Effect of doping the nanoparticles of PγCyD-ZrO_2 into an ECB cell with d = 20μm is shown in Figure A. This figure demonstrates a shift of V-T characteristics in an ECB cell toward the low voltage side by the doping of the nanoparticles of PγCyD-ZrO_2 (0.075wt%) and it is clearly recognized the reduction of birefringence by −10% that corresponds to that of order parameter by −10% due to nanoparticles.

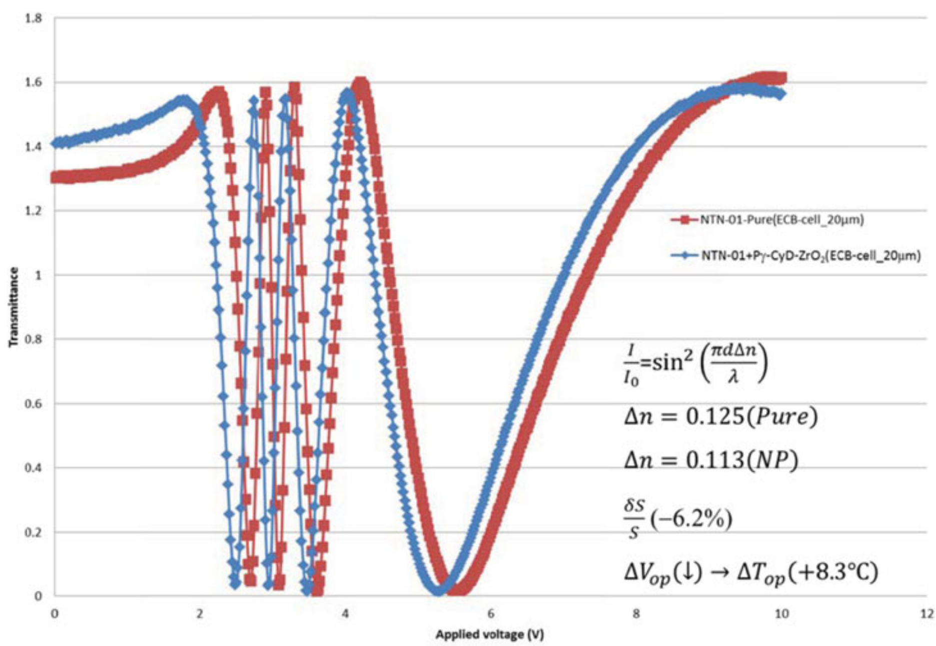

Figure A. V-T curves of ECB cells with d = 20 μm without and with the nanoparticles of PγCyD-ZrO_2 doped into an NLC, NTN-01.