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Improvement of Response Performance of Liquid Crystal Optical Devices by using a Low Viscosity Component *

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Difluorooxymethylene-bridged (CF_2O) liquid crystal (LC) with low viscosity is prepared and used as a fast response LC material. When the material is mixed with isothiocyanato LCs with high birefringence, the visco-elastic coefficient of the mixture decreases evidently and, accordingly, the response performance increases. While the concentration of CF_2O LCs is about 7%, the LC mixture approximately maintains high birefringence and exhibits a fastest response performance that is 14% higher than that of pure isothiocyanato LCs. Therefore, the LC material and mixing method could find useful applications in optical devices.

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Liquid crystal (LC) devices are not only used as display devices but also as optical devices in applications in spatial light modulators,[1] light valves[2] and tunable-focus lenses. For example, spatial light modulators are a type of important component used in adaptive optics systems to compensate for the wave-front aberration caused by atmospheric turbulence in real time and thus can be used to improve the image resolution as close as the diffractive limitation of a telescope. LC optical devices have advantages of higher precision, lower cost, higher reliability and lower power consumption than devices with physical constructions. In the optics applications of LC devices, fast response speed is the key parameter.[3] If the response speed is too slow, the effect of optical imaging will become unsatisfactory.

In nematic LC devices, the LC decay time is the decisive factor of response performance. It can be expressed by the following equation when the LC cell is in parallel-alignment mode,[4]

$$\tau_{\rm decay} = \frac{\gamma_1 d^2}{K_{11}\pi^2}, \tag{1}$$

where γ_1 is the rotational viscosity, K_{11} is the elastic constant and d is the thickness of the LC cell. From Eq. (1), the smaller the visco-elastic coefficient (γ_1/K_{11}) and d, the shorter the response time. However, it is necessary to keep the phase retardation ($d\Delta n$) equal to one wavelength for a liquid crystal spatial light modulator,[5] and then the cell gap can only be reduced to a limited value for a constant birefringence (Δn). Higher birefringence of LC materials enables a thinner cell gap to be used while keeping the same phase retardation and improves the response performance of LC devices. Therefore, LC materials with high Δn and low γ_1/K_{11} can be used to fabricate fast response optical devices. LCs with high Δn always have large viscosity,[4] therefore, high birefringence and low viscosity is in conflict and difficult to be obtain simultaneously. Considering all types of LCs, the LC molecular structures with tolane[6] and isothiocyanate[7,8] groups are a better choice for fast response LC devices, because the γ_1 of these materials is moderate, the Δn is about 0.3 and much higher than common biphenyl LCs. In the further research, higher Δn LC compounds such as phenyl-tolane isothiocyanate ($\Delta n \sim 0.50$) have been used to obtain faster responses.[9] However, it is rarely reported that LCs with a very low rotational viscosity have been mixed with high Δn LCs to improve response performance.

In this Letter, we introduce a type of difluorooxymethylene-bridged LC with very low rotational viscosity to improve the response performance of tolane isothiocyanate LCs (NCS LCs). When the LC compound was mixed with NCS LCs, the response performance could be elevated obviously. The concept of the figure-of-merit (FoM or F) defined and reported by Wu *et al.*,[7] is adopted to compare the performance of different LC compounds. Materials with a high FoM value will provide shorter response times.

$$F = \frac{K_{11}\Delta n^2}{\gamma_1}. \tag{2}$$

The difluorooxymethylene-bridged liquid crystal (CF_2O LC), 4'-propylcyclohexyl-1- difluorooxymethylene-3,4-difluorobenzene, was prepared based on previ-

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ously reported methods,[10] the product was obtained as a slight yellow liquid, its chemical structure is shown in Fig. 1. The γ_1 of CF_2O LC is very low, about 90 cP due to its shorter molecular length and weaker intermolecular interactions than those of common CF_2O materials.[10] In this study, CF_2O LC is mixed with a high Δn LC to decrease γ_1 and to improve the response performance of LC systems. The high Δn LC is an NCS LC solution composed of 4'-alkyl-cyclohexyltolaneisothiocyanate, 4'-alkyl-4-isothiocyanatetolanes and 4'-alkyl-terphenyl-4-isothiocyanate as reported by Gauza *et al.*[8] The Δn of NCS LCs is 0.386 at $\lambda = 589$ nm at room temperature, the γ_1/K_{11} is about $10.0\,\mathrm{ms{\cdot}\mu m^{-2}}$, the FoM is $14.8\,\mathrm{\mu m^2{\cdot}ms^{-1}}$.

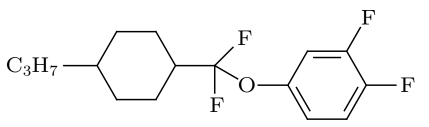

Fig. 1. Molecular structure of CF_2O liquid crystals.

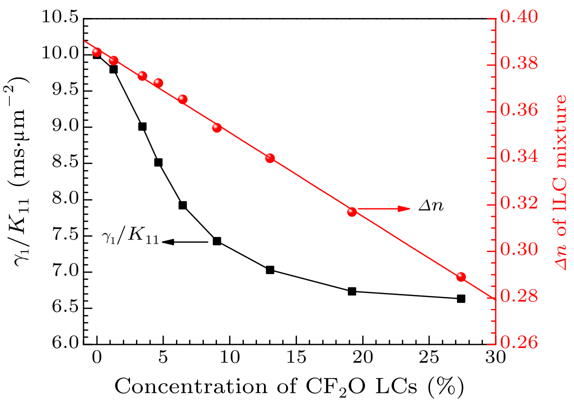

Fig. 2. The visco-elastic coefficient and the Δn depending on concentration of the CF_2O compound.

The CF_2O LCs were mixed with NCS LCs at different concentrations and the properties of the LC mixture were measured at an incident light of $\lambda = 589$ nm at room temperature. Figure 2 shows the visco-elastic coefficient γ_1/K_{11} and Δn (ellipsometer, Jobin Yvon Co.) of the LC mixture. When the concentration increases, the Δn decreases linearly. The straight line in the figure is the linear regression result. In this guest-host LC system, the Δn of the mixture LCs can be expressed as[7]

$$(\Delta n)_{gh} = x(\Delta n)_g + (1-x)(\Delta n)_h, \qquad (3)$$

where subscripts gh, g and h denote the guest-host system, guest LC and host LC mixtures, respectively; x is the concentration of the guest LC. According to Eq. (3), the Δn of the difluorooxymethylene-bridged LC is 0.030. The molecular structure of CF_2O LCs is non-straight and the π-electron conjugation is short; hence, the Δn value of mixture LCs is lower than those of common biphenyl LCs. This Δn value is almost equal to the result of the similar chemical structure.[10]

In order to measure the γ_1/K_{11} of LC mixtures, a series of parallel-aligned LC cells were prepared and injected into LCs with different CF_2O concentrations; the thickness of these cells is $7.76\pm0.02\,\mathrm{\mu m}$. By detecting the decay response time of these cells, we calculate the γ_1/K_{11} value, as shown by the lower curve in Fig. 2. The γ_1/K_{11} value decreases rapidly and finally approaches a constant with the increasing concentration of CF_2O LCs. The γ_1 of NCS LCs is about 200 cP,[8] and of CF_2O LCs is about 90 cP,[10] while the concentration of CF_2O LCs is less than 7%, the γ_1/K_{11} decreases linearly, because the rotational viscosity of the LC mixture can be approximately expressed as the arithmetic average of the components in low concentrations.[11] When the concentration exceeds 13%, the γ_1/K_{11} value saturates to a constant due to the decay of the elastic constant K_{11}.

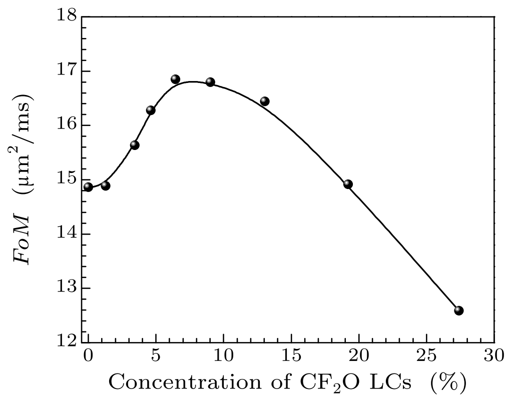

Fig. 3. The FoM value of the guest-host LC depending on concentration of CF_2O LCs.

The FoM value is calculated according to Δn and γ_1/K_{11}, as shown in Fig. 3. The FoM firstly increases and then decreases, with the concentration increasing to 27%. At about 7%, the FoM value reaches a maximum point, about $16.9\,\mathrm{\mu m^2{\cdot}ms^{-1}}$, 14% higher than pure NCS LCs. From Eq. (2), we know that the FoM is decided by Δn^2 and γ_1/K_{11}; when the concentration of CF_2O LC increases to 7%, the γ_1/K_{11} value decays acutely, the Δn decreases linearly but stays relatively high, therefore the FoM value increases. While the concentration exceeds 7%, the γ_1/K_{11} decays slightly, the Δn is kept up to decrease linearly, which results in the decline of the FoM value.

Two LC cell samples with the same phase retardation were prepared to compare the response performance, the cell gaps are 7.35 μm and 7.76 μm, respectively. The cell with cell gap 7.35 μm is injected with pure NCS LCs and the 7.76 μm cell is an NCS LC mixture with 7% CF_2O LCs. The LC cells are sandwiched between two crossed polarizers and the LC directors without an electric field are at 45° with respect to the polarizing direction of the polarizer, while the incident light direction is perpendicular to the substrate. When the voltage ($f = 500\,\mathrm{Hz}$, $V = 3.75V_{\mathrm{rms}}$) are applied at 0 ms and released at 100 ms, transient light intensity was recorded by a photomultiplier and an oscillograph, as shown in Fig. 4. The total numbers for the peak and final point values of each LC cell are the same, which means that the two LC cells possess equivalent phase retardation. When the drive voltage is applied and released, the cell injected LC mixture with 7% CF_2O LCs always shows a higher response speed to reach the final intensity and the response performance is improved significantly.

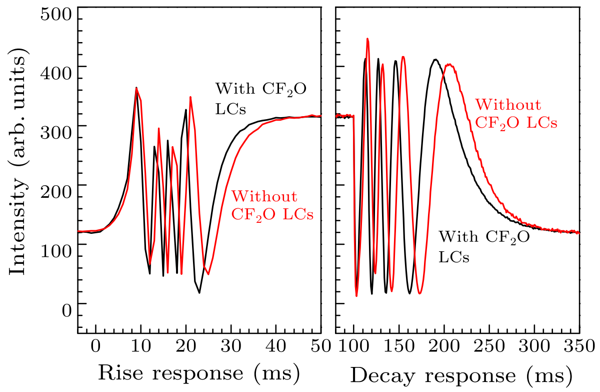

Fig. 4. Transient optical dynamic responses for two parallel-aligned LC cells ($\lambda = 589\,\mathrm{nm}$ and at 21°C; the voltage is applied at 0 ms and released at 100 ms).

In summary, a new LC material with a mixing method for increasing response performance of high birefringence LC is presented. A low viscosity difluorooxymethylene-bridged LC has been prepared and its Δn is only 0.030. When the material is mixed with NCS LCs with a high Δn, the visco-elastic coefficient of the mixture decreases evidently and the FoM value increases from 14.8 to 16.9 $\mu\mathrm{m}^2\cdot\mathrm{ms}^{-1}$ at 7% concentration. The rise and decay response of real LC devices confirms the improvement of response performance. Therefore, difluorooxymethylene-bridged LCs with fast response properties have promising applications in optical devices.

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