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Transmittance variable liquid crystal modes with a specific gray off-state for low power consumption smart windows

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ABSTRACT

For low power consumption smart windows, we developed new ECB and VA mode LC devices with a specific off-state transmittance and an on-state transmittance variable from minimum to maximum values according to applied voltage. The off-state transmittance of the devices could be chosen to be a value suitable for most use time by selecting appropriate retardation values of LC layer and a retarder, which enables considerable reduction of power consumption when applied to devices, for instance, smart windows. The design rules of them were theoretically derived and the electro-optical properties stated above were exposed by corresponding theoretical simulations and experimental measurements.

1. Introduction

Active smart windows are capable of controlling the transmission of sunlight, providing many benefits such as energy saving, eye protection, aesthetic value improvement, and privacy protection when used as windows of buildings and vehicles. Various techniques have been developed for the transmittance variable devices; electrochromic, suspended particle device, liquid crystals [1,2]. As for the representative liquid crystal devices, polymer dispersed liquid crystal and guest-host liquid crystal have been developed for the smart windows [3,4].

Conventional liquid crystal modes such as ECB (electrically controlled birefringence), TN (twisted nematic), VA (vertically aligned) and IPS (in-plane switching) have not been studied well for smart windows because the maximum transmittance of them is low due to use of polarizer. These modes have an advantage of providing sufficiently dark state, almost zero transmittance in addition to low driving voltage, around 5 V.

Above-mentioned all devices except for electrochromic require some power needed to maintain a certain transmittance between the minimum and maximum transmittances obtainable by applying electric power. Therefore off-state transmittance of them is the minimum or maximum in full transmission variation range. If the specific transmittance in between the minimum and maximum transmittances is required for most use time, commonly happened particularly in automobile window application, it is effective for power-saving to show the specific transmittance in voltage off state.

For low power consumption smart windows, we developed new ECB and VA mode LC devices with a specific off-state transmittance and an on-state transmittance variable from minimum to maximum values according to applied voltage. The design rules of new modes and electro-optical properties of them are discussed.

2. Design of LC modes with a specific gray off-state

2.1. New ECB mode

A geometrical and optical configuration of new ECB mode LC cell is shown in Fig. 1: optic axes depicted in Fig. 1(b) are transmission axes of polarizer and analyzer and slow axis of uniaxial retarder. The voltage dependent transmittance of the cell is given by Eq. (1) [5].

$$T(V) = \frac{1}{2}\sin^2(\pi X(V)), X(V) = \frac{\Delta n(V)d - R_o}{\lambda}, \Delta n(0) = n_e - n_o \quad (1)$$

where R_o, n_e and n_o are retardation of the retarder, extraordinary and ordinary refractive indices of the LC respectively.

In the ECB cell that the initial transmittance in voltage-off state is larger than the minimum transmittance and smaller than the maximum transmittance, a point where V is 0 can be indicated by PS1 in the Fig. 2. That is, $X(0)$ may be greater than 0.5 and less than 1. In this situation, when V begins to increase from 0, $X(V)$ decreases from $X(0)$, so the transmittance gradually increases to reach the maximum transmittance

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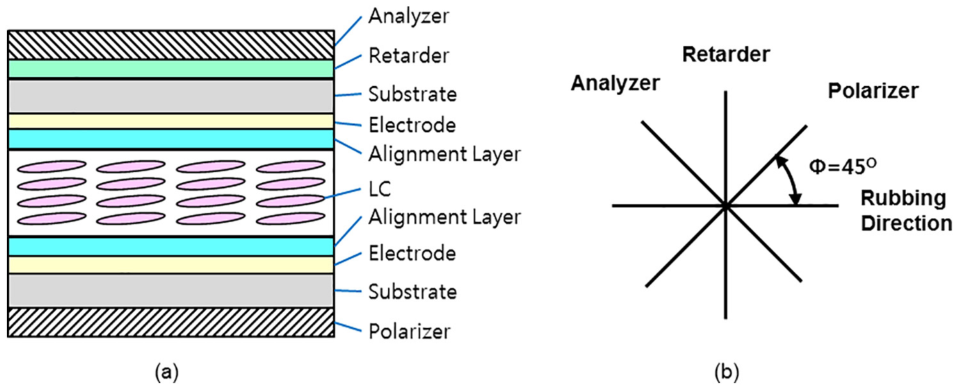

Fig. 1. Configuration of new ECB cell: (a) cross-sectional view, (b) optic axes.

and then decreases to reach the minimum transmittance. In order to ensure that the ECB cell necessarily reaches the minimum transmittance with a voltage less than maximum applied voltage V_{max}, it should appear as indicated by PS2. That is, $X(V_{max})$ must be zero or less than zero. This is because V increases from 0 to reach the maximum value V_{max} at the point where the transmittance is minimum, that is, the point where X reaches 0 or exceeds this point.

The conditions of $X(0)$ and $X(V_{max})$ can be expressed by the following Eqs. (2) and (3).

$$\frac{1}{2}<X(0)=\frac{\Delta n(0)d-R_o}{\lambda}<1 \tag{2}$$

$$X(V_{max})=\frac{\Delta n(V_{max})d-R_o}{\lambda}=\frac{\alpha\Delta n(0)d-R_o}{\lambda}\leq 0 \tag{3}$$

where α is the minimum birefringence ratio of on-state and off-state, usually around 0.2.

From the Eqs. (2) and (3), the following Eqs. (4) and (5) are obtained according to the magnitude relation between $R_0 + \lambda$ and R_0/α.

$$R_o+\frac{1}{2}\lambda<(n_e-n_o)d\leq\frac{R_o}{\alpha},\ \text{for}\ R_o<\frac{\alpha}{1-\alpha}\lambda \tag{4}$$

$$R_o+\frac{1}{2}\lambda<(n_e-n_o)d\leq R_o+\lambda,\ \text{for}\ R_o\geq\frac{\alpha}{1-\alpha}\lambda \tag{5}$$

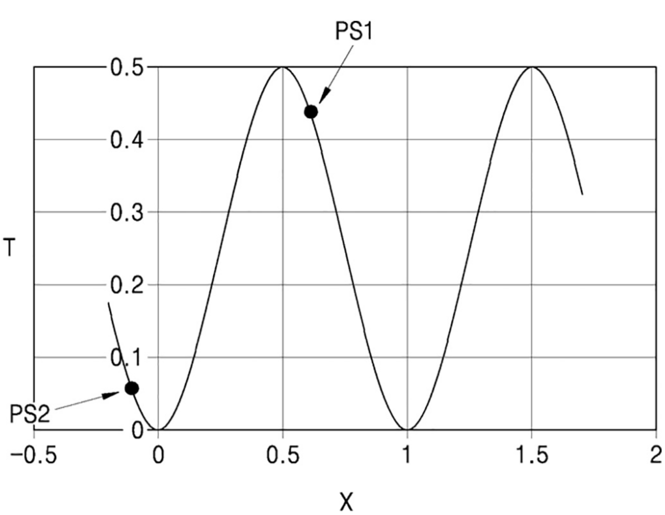

Fig. 2. *X-T* curve of ECB cell written in Eq. (1): PS1 and PS2 indicate initial ($V = 0$) and final ($V = V_{max}$) points.

Of course, as can be seen from Fig. 2, $X(0)$ may be larger than 1 and smaller than 1.5, and $X(V_{max})$ may be 0.5 or less. And $X(0)$ may be larger than 1.5 and smaller than 2, and $X(V_{max})$ may be 1 or less. Hence, Eqs. (4) and (5) can be generalized as Eqs. (6) and (7).

$$R_o+\frac{m+1}{2}\lambda<(n_e-n_o)d\leq\frac{R_o}{\alpha}+\frac{m}{2\alpha}\lambda,\ \text{for}\ R_o<\left(\frac{\alpha}{1-\alpha}-\frac{m}{2}\right)\lambda \tag{6}$$

$$R_o+\frac{m+1}{2}\lambda<(n_e-n_o)d\leq R_o+\frac{m+2}{2}\lambda,\ \text{for}\ R_o\geq\left(\frac{\alpha}{1-\alpha}-\frac{m}{2}\right)\lambda \tag{7}$$

where m is an integer greater than or equal to zero. Eqs. (4) and (5) can be understood as a case where m = 0. By making a ECB cell satisfying the expressions (6) and (7), it is possible to realize a transmittance variable device in which the initial transmittance is larger than the minimum transmittance and smaller than the maximum transmittance and the transmittance can be varied from the minimum transmittance to the maximum transmittance by changing applied voltage.

2.2. New VA mode

Fig. 3 shows a geometrical and optical configuration of new VA mode LC cell.

Optical configuration is the same as that of ECB cell, so similar equations can be derived. Main difference between two modes comes from a change of optical anisotropy according to applied voltage. Specifically, in the VA mode, $\Delta n(V)$ has a minimum value (approximately 0) in off-state, increases as V increases, and finally has $\beta(n_e\text{-}n_o)$. That is, the maximum value of the ratio of the optical anisotropy of the LC layer when V is not 0 for $n_e\text{-}n_o$ can be defined as β, which is approximately 0.8 when a conventional liquid crystal is used. As $\Delta n(V)$ increases as V increases, $X(V)$ also increases as V increases. Therefore, $X(V)$ has the minimum value and the maximum value as shown in the following Eq. (8).

$$X(0)=-\frac{R_o}{\lambda}\leq X(V)=\frac{\beta(n_e-n_o)d-R_o}{\lambda}=X(V_{max}) \tag{8}$$

Fig. 4 is a graph for explaining the condition that the VA cell of Fig. 3 satisfies. Since the initial transmittance at $V = 0$ is larger than the minimum transmittance and smaller than the maximum transmittance, the point where V is 0 can be indicated by PS1 in the graph of Fig. 4. That is, $X(0)$ may be greater than −0.5 and less than zero. In this situation, when V starts increasing from 0, $X(V)$ increases from $X(0)$, so the transmittance gradually decreases to reach the minimum transmittance and then increases to reach the maximum transmittance. The point for the maximum applied voltage V_{max} is indicated by PS2 in the graph of Fig. 4 in order to ensure that the VA cell can reach the maximum transmittance. That is, $X(V_{max})$ must be 0.5 or greater than 0.5. This is because V increases from 0 to reach the maximum value V_{max} at the point where