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Infrared shutter using cholesteric liquid crystal

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In this paper, we propose an infrared light shutter device using cholesteric liquid crystals. The pitch of the device corresponds to the wavelengths of the infrared region with a strong thermal effect. This device is intended for use as a smart window to maintain an optimal indoor temperature by controlling the infrared radiation coming from the sun. The proposed cholesteric device switches between the planar state and the isotropic state by controlling the temperature using an electrically heated transparent electrode made of indium tin oxide. A window with a planar state that reflects infrared radiation would be used mainly in the summer, while the isotropic state that transmits infrared would be applied in the winter. The proposed device produced a variety of gray levels of transmittance based on the temperature, and thus it can provide the proper temperature for each user. The easy fabrication process gives it appeal as a functional device in the smart window market, and it compares favorably with previous light shutter devices. The infrared shutter is expected to be useful for next-generation window applications.

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1. INTRODUCTION

One of the most important things in the conditions of a well-made indoor environment is natural lighting. A well-lit indoor environment brightens the mood, whereas a poorly lit indoor environment can depress the mood. Visible light must enter the house through windows, and the more, the better. Infrared light, which has a strong thermal effect, also affects the mood. Infrared light is a blessing in winter because it makes the indoor environment warmer, but in summer, it can make the indoor environment intolerably hot, especially in cars. Therefore, most people pull down a blind or curtain on the very hot days of summer, but this reduces the amount of visible light entering the indoor environment. Therefore, a functional window device that can control the transmittance of infrared radiation but always transmits visible light is needed.

Cholesteric liquid crystals (CLCs) have been used as a reflective display that does not require a backlight system but uses ambient light as the light source [1–11]. This does not require any polarizer because it does not use the retardation effect, which causes a change in polarization in a general liquid crystals (LC) display. Instead, a Bragg reflection effect that reflects any specific wavelength in accordance with the chiral pitch of LCs in the cell occurs in CLCs. LCs exhibit a Bragg reflection at wavelength $\lambda_o = nP_o$ for normal incidence, where n and P_o are the average reflective index and helical pitch of the LCs in the cell, respectively. Because of this unique optical property of CLCs, they have also been applied to smart windows that can switch the transmission of light by adjusting the reflection [11–20]. If its chiral pitch is fitted to infrared, it can be used as an infrared shutter. However, generally, the reorientation of CLCs operated by an electric field requires a very high voltage to change from a planar to a homeotropic state. Therefore, a small amount of ion impurities in the CLC cell can cause electrical short circuits due to the high voltage, making it troublesome to get good reliability. In addition, the homeotropic state does not show perfect transmission because the LCs' near surfaces barely orient vertically along a vertical field direction due to the strong surface-anchoring energy.

To solve these problems, this paper proposes a CLC infrared shutter whose chiral pitch corresponds to the wavelengths of the infrared region. This shutter is characterized by an electrical heating with a transparent electrode made of indium tin oxide (ITO) that can change the temperature in a CLC cell. The states of the LC are dependent on the temperature. The LC states controlled by the temperature are changed to an isotropic state from a planar state in an initial state. The planar state is used to block infrared light in the summer, and the isotropic state is used to allow the transmission of infrared light in the winter. For these two states, visible light is transmitted through the CLC cell. The CLC device does not have a chance of being electrically short circuited in a high electric field because it is operated within a comparatively low temperature that is not harmful to people. Furthermore, it shows almost-perfect light transmission in the isotropic state.

2. EXPERIMENTAL PREPARATION AND OPERATING PRINCIPLE

Figure 1 presents a schematic diagram of the temperature-controllable cholesteric LC cell for the infrared shutter. The CLC cells were prepared for the experiments using the following process. Glass substrates were cleaned ultrasonically with ethanol and deionized water and dried on a hot plate at 100°C for 5 min. An ITO coating on the bottom glass substrate was used as a heater for each cell. The ITO films were deposited on the glass substrate by RF magnetron sputtering using an indium tin oxide target, which is composed of In_2O_3 (90 wt. %) and SnO_2 (10 wt. %). Deposition was performed in 20 sccm of flowing Ar gas controlled by a mass-flow controller. The working and base pressures of the sputtering system were 9.5×10^{-4} Torr and 2×10^{-6} Torr, respectively. The applied RF power was 20 W when ITO was deposited by sputter. Deposition was carried out at 300°C for 50 min. The thickness of the ITO film was approximately 100 nm. The electrical resistivity of the ITO-sputtered glass substrate was approximately $1.2 \times 10^{-3} \Omega \cdot \text{cm}$. The temperature of the CLC cell was tunable by the electrical current on the ITO conductor acting as a heating material. The ITO-sputtered glass substrates were spin coated with polyimide AL2001 (Nissan Chemical Co. Ltd.) to obtain a homogeneous LC alignment, which was prebaked at 100°C for 5 min and cured at 180°C for 40 min. The polyimide films on the substrates were rubbed with velvet and then assembled for anti-parallel LC alignment. The cell gap of the samples was prepared at approximately 10 μm. The E7 material supplied by Merck was used as an LC in the experiment because the phase transition temperature for the nematic to isotropic of the E7 LC is relatively low (57°C); thus, the power consumption is lower. To generate the LC state with strong chirality in the cells, S811 and R1011, which lead to the left-handed and right-handed chirality of LC, respectively, were used as the chiral dopants. The chirality at room temperature was controlled to produce a central wavelegth of 1064 nm in the spectrum of light reflected on the CLC by the Bragg reflection because the wavelength of the laser source used for the experiment in the infrared region is 1064 nm.

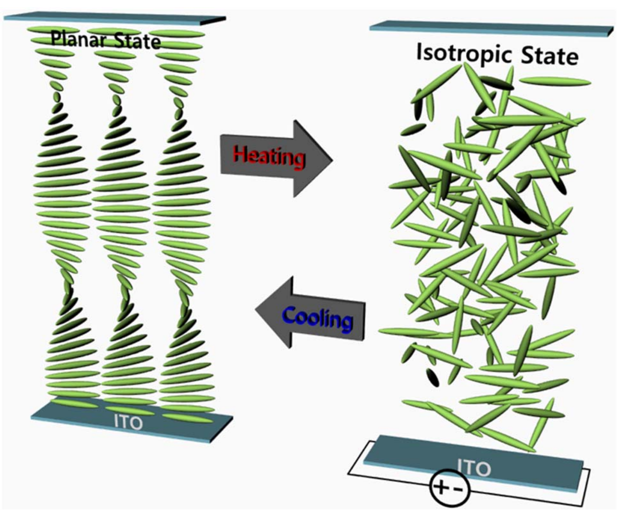

Fig. 1. Schematic diagram of the proposed thermal-controllable CLC infrared shutter.

At room temperature, at which the ITO heater should not be operated, the CLCs strongly reflect infrared radiation with the central wavelength at 1064 nm due to the Bragg reflection. With the increase in temperature, the main wavelength shifts to a shorter wavelength. This may be due to the reduction of the average reflective index of the LCs and depending on the nematic host/chiral additive system. Then, the pitch may increase or decrease as the temperature increases, and the half-width of the spectrum becomes narrow due to the generation of smaller birefringence at higher temperatures. With the increasing temperature, the reflection at the infrared region decreases gradually with the central wavelength shift; thus, the infrared light transmission of the CLC cell is enhanced. Eventually, at the isotropic phase with a higher temperature, the transmission will reach a maximum. Therefore, transmission of infrared light can be tuned and the temperature of indoor environment can be adjusted by controlling the ITO heater accurately with the electrical current.

3. RESULTS AND DISCUSSION

The experiments were conducted to confirm the optical concept of the proposed CLC infrared shutter. Figure 2(a) shows the change in transmittance according to the wavelengths of one CLC cell with left-handed chirality at a variety of temperatures controlled by ITO heating generated from an electric current. As expected, as the temperature increases, the central wavelength shifts gradually to a lower wavelength due to a decrease in the average refractive index of the LCs and an increase in the solubility of the chiral dopant in LCs and the shortened chiral pitch of the LCs. Consequently, the transmittance in the initial central wavelength (1064 nm) within the infrared region increases continuously with the increasing temperature. To display more clearly the temperature tendency of the transmittance at 1064 nm, Fig. 2(b) shows the change in transmittance according to the temperature at the central wavelength (1064 nm). The transmittance at room temperature in the planar state was ca. 50% at 50°C, whereas it was ca. 95% in the isotropic state. The transmittance in the isotropic state was very high. Therefore, it can absorb a large amount of infrared light, which creates a warm indoor environment from the heating of ITO during the winter. Here, the 50% transmittance at room temperature is because the CLC cell allows only the circularly polarized light coinciding with helical direction of the CLCs to pass, and the circular polarization with the same handedness as the helical structure is reflected by the Bragg reflection. In the present case, the CLC cell with left-handed chirality transmits only left-handed circularly polarized light, resulting in 50% transmittance.

For comparison, a conventional CLC cell switched by an electric field was fabricated, and the transmittance was measured according to the applied voltages. Figure 3(a) shows the change in transmittance according to the wavelengths of one

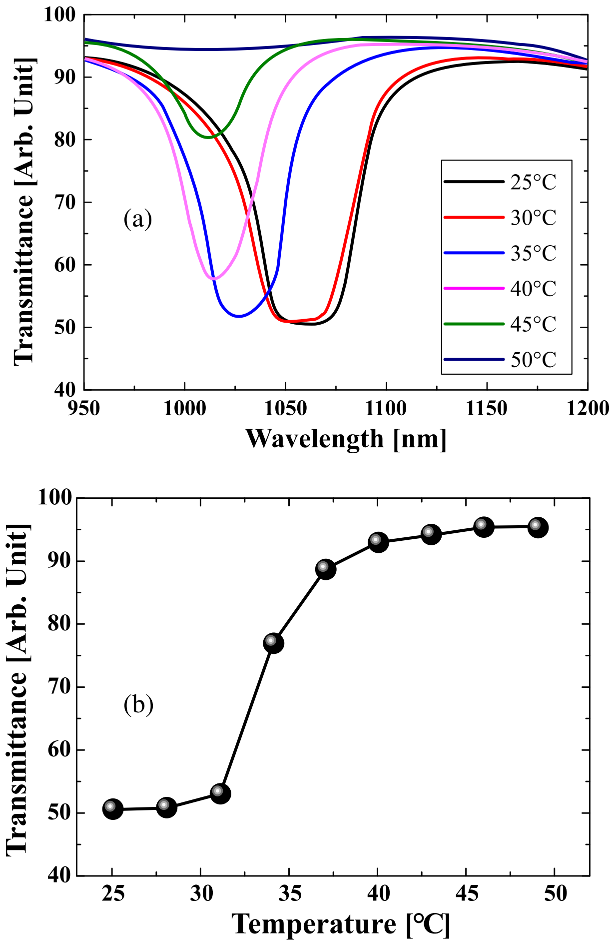

Fig. 2. (a) Change in the transmittance according to the wavelengths of one CLC cell with left-handed and chirality at variety of temperatures. (b) Change in the transmittance according to temperature at the main wavelength of 1064 nm.

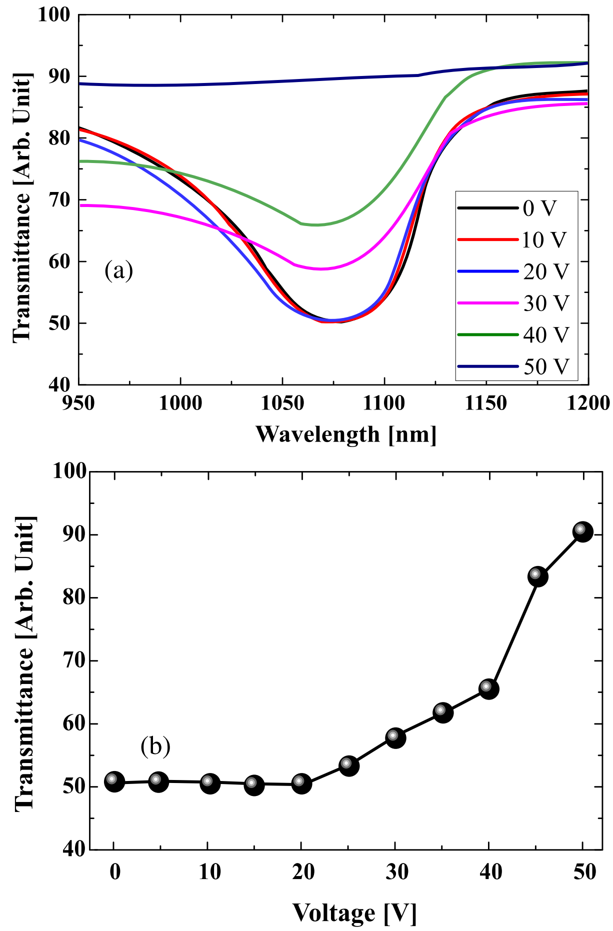

Fig. 3. (a) Change in the transmittance according to the wavelengths of one CLC cell with left-handed chirality at a variety of voltages and (b) change in the transmittance according to voltage at the main wavelength of 1064 nm.

CLC cell with left-handed chirality at a variety of voltages under room temperature (20°C). No shift in the central wavelength was observed regardless of the applied voltage, but at voltages higher than the threshold voltage, the transmittance increased gradually and became ca. 90% at 50 V, which is a very high voltage for the operation of an LC device. While the proposed CLC cell had a transmittance of 95% in the isotropic state, the conventional CLC cell barely showed a transmittance of 90% in the homeotropic state with a high voltage because the homogeneously aligned LCs on both surfaces of the cells do not move in the vertical direction even in a strong electric field due to the great anchoring strength. To achieve a transmittance greater than 90% in a conventional CLC cell, a voltage of more than 200 V should be applied to the CLC cell. Under such a high voltage, ion impurities in the CLC cell can cause electrical short circuits by the very strong electric field, which may be dangerous to humans. Therefore, the proposed CLC cell may be suitable as an infrared shutter. The removal of 50% of the incident light may not be sufficient for an indoor environment in very hot tropical areas. They may require the removal of a large amount of incident lights. Therefore, one more CLC cell with a right-handed CLC cell was used to reflect the lift-handed circularly polarized light and to remove most of the incident light.

Figure 4 shows the change in transmittance according to the wavelength of incident light in two CLC cells with left-handed and right-handed chirality over a variety of temperatures controlled by ITO heating generated from an electric current. As expected, when two CLC cells were used, the transmittance in the planar states of the two CLC cells decreased by ca. 16% by reflecting the right-handed circularly polarized light, even though the transmittance in the isotropic state had decreased slightly. Here, the transmittance of 16% may be due to interfacial reflection and the imperfect circular polarization of light coming out from first CLC cell and the existence of a very small amount of focal conic states, which generate a scattering effect. Consequently, by using two CLC cells, the infrared light can be blocked effectively and adopted in hot areas.

Finally, the actual temperature-controlling effect was examined using the proposed CLC cell. Figure 5 shows the change in indoor temperature according to the laser exposure time for three samples: a conventional glass window, one CLC window, and two CLC windows. A laser beam of wavelength 1064 nm

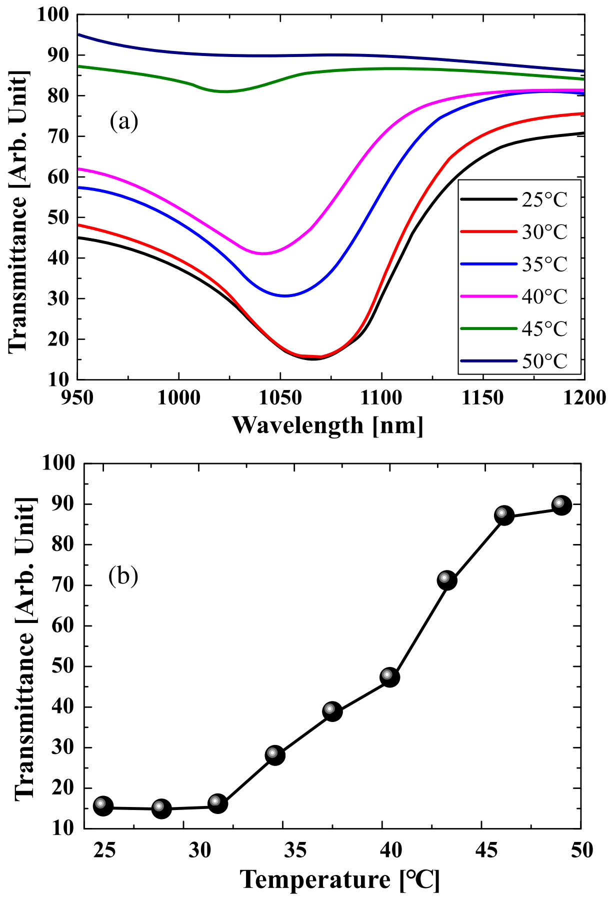

Fig. 4. (a) Change in the transmittance according to wavelengths of two CLC cells with left-handed and right-handed chirality at a variety of temperatures and (b) change in the transmittance according to temperature at the main wavelength of 1064 nm.

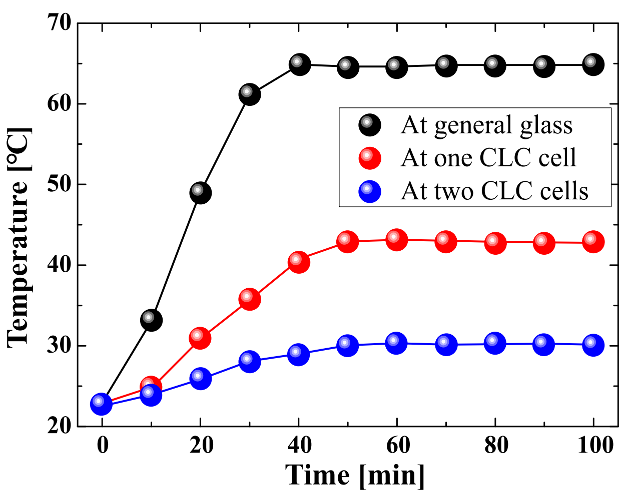

Fig. 5. Change in the indoor temperature according to the laser exposure time for the three samples: conventional glass window, one CLC window, and two CLC windows.

was exposed to the three types of windows in a fabricated miniature house that was 3 cm × 3 cm × 3 cm in size. The indoor temperature was measured using a thermocoupler as a thermometer. In the case of the conventional glass, the indoor temperature increased by approximately 65°C. On the other hand, the indoor temperatures with one CLC cell and two CLC cells increased by only 43°C and 30°C, respectively. This indicates that the indoor temperature can be controlled by blocking or transmitting infrared using the proposed CLC cell. In summer, with the hot weather, the applied power for the proposed CLC shutter is zero because the planar state with the stable state is used to block the infrared. Thus, in summer, we can save the power for the operation of an indoor air conditioner. So the power is required just in winter, when infrared can be transmitted by the isotropic phase with a higher temperature. Then, in the case of our CLC window with a size of 3 cm × 3 cm, the applied power used was 0.5 W to elevate about 20°C when a 5CB LC with a lower phase transition temperature (39°C) was used. Therefore, if we used the CLC window with conventional window size of 1 m × 1 m, then the required power will be about 1000 W. However, this power also plays a role in increasing the indoor temperature. So this CLC shutter can be regarded as a heater combined with infrared.

In addition, it may be cumbersome and expensive to use two CLC cells to reduce the transmittance. Therefore, one CLC cell and one CLC film with a fixed planar state can be adopted in very hot areas to reduce the cost. Because there is warmth even in winter, a transmittance of 50% during the winter will be sufficient to produce a pleasant indoor temperature. On the other hand, in very cold areas, only one CLC cell can be used. Because it is cool even during the summer, a transmittance of 50% during the summer will give a feeling of well-being to humans. They can be used appropriately depending on the location. If we use LCs with a very high birefringence of more than 0.4 or adopt a broad-band cholesteric with a polymer network using reactive mesogens, the CLC window will cover the near IR-region from 800 to 1200 nm. If we use one CLC window and one CLC film, it covers infrared regions from 800 to 1200 nm and 1500 to 1750 nm, which correspond to IR regions coming to earth from the sun.

The RavenWindow from RavenBrick (Denver, Colorado) does not require any power during any season. On the other hand, our CLC window does not require any power just during warmer seasons, but it does in cooler seasons. In terms of energy savings, the RavenWindow is better on cooler days. However, the RavenWindow blocks visible light as well as IR because it uses a thermochromic filter, and thus, we cannot clearly see the outside scenery in the summer. On the other hand, our CLC window can transmit visible light always in both the summer and winter. Thus, we can clearly see the outside scenery even in summer and will also boost our moods in the bright environment. In addition, the proposed CLC window can control the transmittance of IR.

4. CONCLUSION

We examined a CLC infrared light shutter device. The proposed CLC device was switched between the planar state and the isotropic state by controlling the temperature of electrically heated ITO. The proposed device produces a variety of gray levels of transmittance depending on the temperature, which can be used to provide the proper temperature. The experimental results show that the proposed CLC cell with thermal action can control the indoor temperature by blocking or transmitting infrared radiation. The infrared shutter is expected to be useful for next-generation window applications.

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