Infrared reflector based on liquid crystal polymers and its impact on thermal comfort conditions in buildings

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ABSTRACT

There has been a huge increase in the global demand of energy over the last few years. One of the main contributors to energy consumption in buildings, cars, greenhouses and indoor spaces is the cooling devices needed to maintain the indoor temperature at comfortable levels. To reduce the energy used by cooling devices, we need improved light control in transparent building elements, such as windows. Infrared (IR) reflectors applied to the windows for rejection of infrared light would be very attractive, especially if they do not affect light in the visible region.

A method to selectively and precisely control infrared transmission is via the use of cholesteric liquid crystal (Ch-LC) polymer reflectors. Ch-LCs, also known as chiral-nematic LCs, reflect circularly polarized light as a result of their self-organizing molecular helices. The pitch of the helix in these networks determines the wavelength of reflection. In contrast to existing alternatives, they are characterized by a very sharp cut-off between the transmissive and the reflective state enabling exact tailoring of the heat reflection. In this article we have focused on fabrication of infrared reflectors using Ch-LCs and a computational model was used to predict the energy savings of this IR-reflector in an office building in Abu Dhabi which indicated that 6% energy savings can be realized.

Keywords: cholesteric liquid crystals, infrared reflector, circularly polarised light

1. INTRODUCTION

With increasing global warming, energy consumption by cooling devices (i.e. air conditioners) is increasing rapidly to maintain indoor temperatures in the comfortable zone.1 Simulations predict that by the year 2100 the consumption of air conditioners will increase 74%.2 These cooling devices are one of the most expensive energy consumers in buildings so, alternatives which can maintain comfortable indoor temperatures are in great demand.3 Several alternatives, including shutters,4 blinds, photochromic windows,5,6 switchable windows based liquid crystals7 and metallic coatings8 have been studied to reduce the use of cooling devices. Solar infrared radiation which contributes to passive solar gains in buildings ranges from 700 nm to 1 mm, whereas visible light from 350 nm to 700 nm is necessary in our working and living zones. Interestingly, solar infrared radiation from 700 to 1100 nm comprises more than 60% of total infrared energy. In this paper, we have fabricated a Ch-LC infrared reflector which reflects solar infrared energy from 700 to 1100 nm without interfering with the visible region. The wavelength of light reflected by a Ch-LC is determined by its helical pitch. The single-pitch Ch-LC reflects wavelength of light with wavelengths between $\lambda_{\text{max}} = n_e*P$ and $\lambda_{\text{min}} = n_o*P$. Here $n_e$ and $n_o$ are the extraordinary and ordinary refractive indices and P is the pitch of the Ch-LC. The bandwidth of the reflected light is given by $\Delta\lambda = \lambda_{\text{max}} - \lambda_{\text{min}} = (n_e-n_o)*P$, which for single-pitch Ch-LCs is narrow and varies from 30 to 120 nm, depending upon the LC mixture.9 Several methods have been established

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to enhance the bandwidth of reflected light.\textsuperscript{10-13} We have used photoinduced diffusion during photopolymerization to achieve the broadband in the fabrication of IR reflector.\textsuperscript{14} Ch-LC also possesses the inherent property of handedness selective reflection of un-polarised light.\textsuperscript{10} The total reflection of unpolarised light from single Ch-LCs cannot be greater than 50% due to reflection of only one handedness of incident circularly polarized (CP) light and transmission of the opposite handedness. Several methods have been shown to enhance the reflection limit to 100\%\textsuperscript{15-18}.

In this article, we report the fabrication of a Ch-LC based IR-reflector which reflects solar infrared light from 700 to 1100 nm with complete transparency in the visible region. We also present the potential impact of the fabricated IR reflector on the indoor environment of buildings and its impact on the primary energy consumption with simulations of an office building employing Ch-LC windows.

2. RESULTS & DISCUSSION

Liquid crystal DB-335 and DB-162 were synthesized as reported earlier.\textsuperscript{9,10} Two mixtures were used to fabricate an IR reflector. Scheme 1 shows the chemical structures of liquid crystals and mixtures used. Chiral dopant DB-335 was added to DB-162 to form the cholesteric liquid crystal. The helical twisting power of the chiral dopant was found to be 4.1 $\mu$m$^{-1}\textsuperscript{1,10,14}$ so 28\% of chiral dopant was used in both the mixtures to have reflection peak centered around 900 nm. Photoinitiator Irgacure-651 was used to polymerize the cholesteric phase at 105 $^\circ$C by UV light of wavelength 365 nm. In a second mixture 1\% of Tinuvin-328 was added to obtain a broadband reflector by photoinduced diffusion.

![Scheme 1. Chemicals used to fabricate Ch-LC infrared reflectors. The mixture consisted of chiral dopant DB-335, nematic mesogens DB-162, Tinuvin-328 and Irgacure-651.](image_url)
Mixture used are:
Mixture I- 71% DB-162, 28% DB-335 and 1% Irgacure-651.
Mixture II- 70% DB-162, 28% DB-335, 1% Irgacure-651, and 1% Tinuvin-328.

The mixture was used to fill a cell of gap thickness 6 μm via capillary action. A Differential Scanning Calorimetry (DSC) spectrum of mixture 1 (Scheme 1) shows the cholesteric LC phase of the mixtures from 79 °C to 153 °C (Figure 1(a)). The Ch-LC phase was further confirmed by the oily streak texture of the mixture 1 at 105 °C (Figure 1(b)).

![Figure 1](image1.png)

Figure 1. a) Differential Scanning Calorimetric (DSC) spectrum of mixture 1 shows a cholesteric phase from 79 °C to 153 °C. b) Optical microscopy images of the mixture 1 at 105 °C confirm the cholesteric phase of liquid crystal.

Figure 2 (a) shows the transmission spectrum of mixture 1 after photo-polymerization by exposing to UV-light of intensity ~7.5mW/cm². The reflection bandwidth of film 1 was 110 nm with the peak centered at 875 nm. This bandwidth was too small to reflect substantial amounts of infrared light. To achieve broadband infrared reflection, a UV-intensity gradient was obtained through the film depth by adding 1% UV-absorbing dye Tinuvin-328 to mixture 1 resulting in mixture 2 (Scheme 1). Upon UV irradiation, due to the intensity gradient, diacrylate (bi-functional) molecules (DB-335) undergo faster polymerization at the top of the film (closer to the light source) compared to the bottom. This creates a depletion of diacrylate molecules at the top side and thus results in the diffusion of diacrylate molecules from bottom to top. Such diffusion causes an uneven concentration distribution of chiral dopant (DB-335) throughout the film and thus a pitch gradient is attained in the film depth.

![Figure 2](image2.png)

Figure 2. Transmission spectra of mixture (a) 1 after UV polymerization; mixture (b) 2 after photoinduced diffusion (Inset) Photograph of the cells demonstrate the clarity of the samples for visible light.
To obtain the bandwidth around 275 nm, mixture 2 was illuminated by UV light of intensity $\sim 1.3 \times 10^{-5}$ W/cm² at 105 °C for 3 min. Thereafter, the sample was post cured with flood exposure of UV light of intensity $\sim 7.5$ mW/cm². A bandwidth of 260 nm was obtained by photoinduced diffusion as shown in figure 2(b). Film 2 reflects a range of right handed CP infrared light from 700 to 1100 nm and is still completely transparent in the visible region (Inset figure 2(b)).

Figure 3: Schematic diagram of the window used for simulations; Inside and Outside represents the indoor and outdoor places.

To investigate the impact of the fabricated IR reflecting polymer film incorporated into the building envelope, we carried out a study using building energy simulation programs. Our main indicators of interest were energy performance and indoor comfort conditions. First, the experimentally determined reflection and transmission spectra as a function of incidence angle for the Ch-LC reflectors were imported in the program Optics (Version 6.0). The data was then used for creating a double layer glazing system including a 12.7 mm thick cavity filled with argon in Window W6 (Version 6.3). Window also calculates the transmission, absorption and reflectance properties of the double glazing unit for different incidence angles of solar radiation. For this study, the glass with the IR reflecting polymer was embedded between 2 glass sheet with a thickness of 3 mm each (figure 3). The glass sheets used had a transmittance (Tₘ) of 0.83.
Figure 4. Solar irradiation (four orientations, left axis) and exterior dry bulb temperature (right axis) for Chicago and Abu Dhabi during two days in summer (a-b) and two days in winter (c-d).

We assessed the performance of the glazing systems with and without IR reflecting coatings using dynamic building simulations carried out in the program Trnsys v17. Table 1 gives an overview of the properties for both window types. Here, U- and g- values represents heat transfer coefficient and solar energy transmittance coefficient of glass, respectively. For the simulation we considered a three storey standard medium sized office building with a window-to-wall ratio of 48 %. The building (5000 m²) is defined by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) as part of the set of Commercial Reference Building models. 23 The infiltration and ventilation rates and the internal heat gains for a typical office building were taken from ISSO guidelines 32. We assumed a cooling set point of 26 °C and a heating set point of 20 °C. Apart from the IR reflector, no other solar shading systems were modeled.

Table 1: Overview of material properties used in the simulations.

<table>
<thead>
<tr>
<th></th>
<th>U-value</th>
<th>T_{sol}</th>
<th>T_{vis}</th>
<th>g-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear glass</td>
<td>2.73</td>
<td>0.737</td>
<td>0.828</td>
<td>0.797</td>
</tr>
<tr>
<td>IR reflector</td>
<td>2.73</td>
<td>0.649</td>
<td>0.828</td>
<td>0.698</td>
</tr>
</tbody>
</table>

In the simulations, four different façade orientations were considered, for the climates of Chicago, USA and Abu Dhabi, UAE. Chicago has a continental climate, with cold winters and relatively warm summers. The climate of Abu Dhabi can be characterized as hot and arid. Figure 4 compares the weather conditions in both
locations for two characteristic days in winter and summer. Levels of direct solar radiation are to a large extent variable. It depends on other factors such as the temperature difference between inside and outside, and the amount of internal gains, whether the solar gains make a valuable or unwanted impact. To investigate these effects, we first analyzed the different contributions to the building’s energy balance. In a second phase, the energy saving potential for space heating and cooling was assessed.

Figure 5. Zone energy balance for a glazing system with (left) and without (right) IR reflector. The results represent two days in summer for the east facing office zone located in Chicago.

Figure 5 shows the energy balance of the office building in Chicago for the east facing façade. As can be seen in this Figure, the peak in solar gains occurs early on the day due to the orbit of the sun. The Figure shows that application of the IR reflector effectively reduces solar heat gains. On sunny days, as shown here, the difference goes up to 15 W/m² floor area. As a result, there is a reduction in the cooling energy that is needed to keep the space comfortable. In summer, the reduction of the cooling load and solar heat gains due to the IR reflector are in the same order of magnitude for Chicago and Abu Dhabi. The decreases in both cases are linear for the different glazing systems but show a greater decline for the solar gain than for the cooling demand. This is due to internal loads such as computers and other electrical devices which produce heat and whose values are independent of the solar irradiation.

Figure 6 shows a breakdown of energy consumption for the locations of Abu Dhabi and Chicago for the different orientations and different window types. The results show a reduction in energy demand for all façade orientations in Abu Dhabi (Figure 6a). In this hot climate, there is no demand for space heating, so the reduced admittance of solar gains contributes to energy-saving all year long. Figure 6b, on the other hand, shows that for Chicago there is a reduction in energy consumption for all orientations except for the north façade, which experiences an increase in energy consumption due to a greater heating demand, which is larger than the energy savings for cooling. Due to a higher angle of incidence at the south façade, there the energy consumption stays almost constant, while for east and west which experience more solar irradiation the windows with a larger reflection component help to reduce the total energy consumption.
Figure 6. Heating and cooling energy demand per orientation for Abu Dhabi (left) and Chicago (right). Clear represents the case without the Ch-LC IR reflector, and IR represents the case with the Ch-LC IR reflector.

In many climates, the IR layer has an effect not only on cooling load and overheating risk, but also influences heating energy consumption. Due to its lower solar transmittance, the positive contribution of useful solar gains in the winter season also reduces. Depending on climatic conditions and use of the building, this negative effect can sometimes counterbalance the positive contributions. It would be interesting to investigate the potential of a window coating with controllable near-infrared transmission characteristics. By developing such a climate adaptive glazing system\(^\text{[22]}\) that switches from a more transparent state to a reflecting state, this problem could be reduced. In winter the solar heat from the sun could contribute in reducing the heating demand and by blocking a part of the infrared light there could be a decrease in the cooling demand during warmer days.

The simulations studies here were all done without using additional shading systems. In reality, it could be possible that these solar shading systems are necessary to protect people in the office space from glare which contributes to the comfort of the user. This implies that even though there is no shading device necessary to keep the solar heat outside, it could still contribute to a reduction in the cooling demand if these devices are used.

3. CONCLUSION

We have described the fabrication of an infrared reflector based on cholesteric liquid crystals. The fabricated infrared reflector reflects solar energy over a broad infrared region from 700 nm to 1100 nm, which consists of more than 60% of total infrared energy. Simulation shows that having the fabricated IR reflector coated over windows can lead to a significant impact on indoor temperature and energy savings. The glazing system shows the biggest potential in warm climates where no heating is needed. For an office building in Abu Dhabi, the glazing system leads to a reduction in cooling energy of up to 6.3%, and therefore a significant contribution to reduced CO\(_2\) emissions and operating costs of a building, without the drawbacks of conventional shading systems. In colder climates, glazing systems with IR reflection contribute to a reduction in the cooling demand. Unfortunately, at the same time there is an increase in the heating demand.

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REFERENCES