Replicated structures for switchable liquid crystal beam control devices

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Title: Replicated structures for switchable liquid crystal beam control devices

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Abstract: Active beam shaping is considered for various lighting applications. One of the possible applications is video flash where the width of the light from a LED flash is coupled to the zoom function of the camera. This means that when an object is at a distance of 7m it is sufficient to have a bundle with a width of 2*10°. However at a distance of 2 m the beam width needs to be increased to more than 2*30° while remaining sufficiently homogeneous. Here we describe various strategies using replicated structures which can be combined with liquid crystals for switchable beam width function.
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1. Introduction

Beam shaping is considered for various lighting applications. One of the possible applications is related to video flash where the width of the light from flash is coupled to the zoom function of the camera. This means that for an object to be filmed at a distance of 7m beam width of $2\times10^\circ$ is sufficient while at a distance of 2 m the beam width needs to be more than $2\times30^\circ$.

For this purpose use of liquid crystal optics have been suggested. One of the principles which is considered is based on switchable lens arrays. In this principle a collimated beam of light is broadened using a lens array. However there is a fundamental issue regarding the lens array in combination with a beam of light which is divergent. The resultant beam shape of the divergent light source when it is combined with a lens array is a luminance, which is very un-uniform. This is simply because the resultant beam is a convolution of the lens array response and the incoming beam as illustrated in fig1 a and b. Figure 1(a) illustrates what would happen if a single large lens is used. The beam with a block form with a width of $2\theta_1$ would increase its width to $2(\theta_1 + \theta_2)$. However if a lens array is used the result is a convolution of the beam and the response of the lens array. Figure1b schematically illustrates what would happen to the beam shape illustrated in this figure. It indicates that the use of a lens array in combination with a divergent beam results in a increase in the beam width from $2\theta_1$ to $2(\theta_1 + \theta_2)$ however at the same time the shape of the beam is changed and sloping flanks with a width of $2\theta_1$ is introduced.
One of the possibilities for compensating for this effect is to adjust the response of the array by designing it in a desired way. The well-known method for doing this is based on the replication technology. In this technology an optical design based on geometrical optics in order to obtain the desired optical effect is made and formed in a transparent substrate. This is then immersed in a LC cell as schematically shown in Figure 2. The

**Figure1** Schematic representations response to a beam with a certain shape to A) a single lens B) a lens array.
ordinary refractive index of the LC is chosen to be the same as the refractive index of the substrate so that in the field off state the effect is present for one of the polarization directions which becomes refracted (Figure 2(a)). Applying an electric field induces the alignment of the molecules in the direction of the electric field and as a result the optical effect disappears (Figure 2(b)). However if the grooves of the surface relief structure are not in the direction of rubbing then the effect is inhomogeneous as explained below.

Figure 3 shows a liquid crystal cell with a Fresnel lens structure. It has a curvature in the rubbing direction of the orientation layer as well as perpendicular to it.

**Figure 2** Liquid crystal cell with a surface relief structure in the field A) off B) on states.
In figure 3 the average angles of the lens curvature are projected to a plane. It can be seen that the top angles become steeper as we diverge from the center of the lens. As the LC lens is based on pure refraction one can calculate the divergence of the ray falling perpendicular to the substrate based on angle $\alpha$ (related to a position within the lens) as defined in figure 2.

Figure 3 Liquid crystal fresnel lens A) Top view B) Cross-section in Y direction C) Cross-section in X direction.
Using Snell's law we calculated the deflection angle $\theta$ for various In figure 4 deflection angle $\theta$ is plotted as a function of top angle $\alpha$ of the structures for two cross sections shown in Figure 3.

![Figure 4: Deflection angle $\theta$ as a function of top angle $\alpha$ of prismatic structures shown in Figure 2 calculated for the cross-sections X and Y shown in Figure 3.](image)

The effective extraordinary refractive index is calculated according to the equation 1

$$n_{\text{e}(\text{eff})} = \frac{n_{\text{e}}n_{\text{o}}}{\left\{ (n_{\text{o}}^2 \cos^2(a) + n_{\text{e}}^2 \sin^2(a)) \right\}^{0.5}} \quad 1$$

In Figure 4 it can be seen that the deflection angle is very much dependent on the cross section. The cross-section Y can give high deflections while deflections to be obtained from cross-section X will not expected to exceed 10°. In the case of cross-section Y the large deflection angles >35° required for the video (θ) can only be obtained for structures with top angles (α) in the range of 34-36°. Even if we consider that light coming out
of the flash collimator will be around 2\*5 in order to avoid total internal reflection the top angle of the structures should not be more than 39°. This will give us a deflection angle (θ) of 30° which might be just enough. We also estimated the deflection angle (θ) as a function of (φ) (see fig.3(a)) for different (α) and the results are shown in figure 5.

**Figure 5** Deflection angle as a function of angle φ (see fig.3(a)) for α= 34° and 40°.

Here again it can be clearly seen that the deflection angle is very much dependent the orientation of the groove with respect to the orientation direction of the molecules as indicated by (φ) in the above case. Furthermore the required deflection angles can only be obtained in a small range of (φ). Here it is also important to point out that only for φ=0° and 90° the linear polarization state of light is preserved. For other angles light becomes elliptically polarized. As double cell configuration is necessary for influencing both polarization directions configurations where the linear polarization is altered are not acceptable.

In figure 6 we consider various shapes for the surface relief in the form of linear groves. Grove lines are crossed in this way both polarizations are influenced furthermore we use two sets of groves for space filling. Figure 6 also shows schematically 2-D intensity
distribution and indicate the response of the two crossed structures which are rotated 45° with respect to each other. It can be seen that if a profile A is used then there will be a hot spot in the middle with an intensity four times as high as the side. On the other hand if profile B is used there will be a hole in the middle. We therefore suggested the use of profile C with a flat top to obtain a more homogeneous distribution. Of course there are variations in this theme possible such as combination of blank areas within the cell, which just transmit the beam without altering it. It is also possible to use B when double cell configuration is used for un polarized light (see below). In that case orientation direction of the molecules are not totally crossed or a retardation film is placed in between the cells so that part of the light is not influenced by the second cell.

<table>
<thead>
<tr>
<th>Surface relief profile</th>
<th>Input beam profile</th>
<th>Response to two crossed directions</th>
<th>Resultant beam profile</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td></td>
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<tr>
<td>B</td>
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<td>C</td>
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*Figure 6* Grove profile and schematic representation of a beam of light to two crossed groves rotated 45° with respect to each other.

In Figure 7 we show the cross-section of the suitable microstructures. In Figure 8 we shows the top view of the structures, which need to be placed on top of each other. In this figure the lines indicate the direcction of the groves and the LC molecules are oriented in the direction of the groves.
Another possibility is to use structures shown in fig.7 in a single cell. In that case instead of isotropic layers birefringent replica layer needs to be used. Furthermore the replica layers shown in Figure 8 must be on the surfaces within the LC cell in a twisted nematic configuration.
2. **Results and discussion**

The structure proposed in Figure 7 was produced at Apptech. It was subsequently replicated using a mixture of ethoxylated bisphenol A diacrylate and hexan diol diacrylate and an scanning electron micrograph of the structure is shown in Figure 9. The mixture after polymerization had a refractive index of 1.53.

![Figure 9 Scanning electron micrograph of the replicated structure.](image)

In Figure 9 it can be seen that the flat part had a width of 10μm which is twice of that what we needed. The replicated structure was coated with a polyamide layer which was then rubbed in the direction of the grooves. The cells were then filled with a liquid crystal BL009 with refractive indices of $n_{o}=1.5266$ and $n_{e}=1.8181$. We then placed two cells on top of each other and glued them with index matching glue so that the groves in the cells were perpendicular to each other and used it for various characterizations.

In Figure 10 the transmission and reflection/absorption for the cell is plotted as a function wavelength in the electric field off state.
Figure 10 Transmission and reflection /absorption for the cell is plotted as a function wavelength in the electric field off state.

This figure shows that a large portion of light is not transmitted and partly it becomes reflected and partly it is absorbed. It can be seen that at long wavelengths the major cause of the reduced transmission is reflection. However at wavelengths above 500nm losses due to absorption rapidly increases and exceeds the reflection.

We used Eldim to characterize the cells and in Figure 11 shows the angular luminance distribution for a beam of light with high degree of collimation after passing through the double cell. This figure as expected the presence of five spots can clearly be seen

Figure 11 Angular luminance distribution for light after passing through the cells.
The intensity profile along a line going through the spots is shown in Fig12.

![Intensity profile along a line going through the spots](image)

**Figure 12** *Intensity as a function of angle for a beam of light going through the crossed cells.*

This plot shows that the central intensity is about 2 times lower than the side peaks. One can try to draw the conclusion that this is the desired situation as when this crossed cells is combined with the second pair where the lines are rotated by 45° one would increase the central intensity by a factor two while the intensity of the side peaks would stay the same. However as this beam patterned is projected onto a flat surface there is a factor \(\cos(\theta)^3\) which we need to account for originating from correcting for the distance and the surface which is at an angle to the beam.

We repeated the measurement using a beam of light form a collimated LED source and the and the angular luminance distribution is shown in Figure 13.

![Angular luminance distribution](image)

**Figure 13** *Angular luminance distributions on a flat surface for a beam from a led source after passing through the cells.*
In this figure the intensity profile along the vertical and horizontal lines are plotted as a function of angle

![Graph showing illuminance as a function of angle](image)

**Figure 12** Illuminance measured on a flat along the vertical and horizontal lines as a function of angle.

This figure clearly illustrates the effect mentioned earlier showing that in the central part the illuminance is higher than what would ideally be needed (half of that measured for the side peaks). This again shows the effect of the flat part of the surface relief structure being 10μm instead 5μm.

![Angular luminance distributions](image)

**Figure 13** Angular luminance distributions on a flat surface for a beam from a led source after passing through two pairs of crossed cells as indicated in Fig.8.
We finally show the angular luminance distribution on a flat surface for a beam from a led source after passing through two pairs of crossed cells as shown in Fig.8. In this figure it can be seen that the shape of the pattern has a star form but by fine tuning of the structure this can be improved.

**Figure 14** Illuminance measured on a flat along the vertical and horizontal lines as a function of angle.

**Figure 15** Photograph of the surface illuminated by the LED source with the beam shaping element.

In figure 14 Illuminance measured along the two axes are plotted as a function of angle. In this figure the presence of the hot spot in the center can clearly be seen. As mentioned earlier this is due to the production mistake originating from the flat regions being 10μm.
instead 5μm. The green line in this figure shows the level which would be observed with the correct design. In that case a more homogeneous illuminance on the flat surface would be obtained. Finally in figure 15 we show a photograph of a surface illuminated by the LED source with the beam shaping element. Here in the addition to hot spot there is a large color uniformity. This is caused by the dispersion in the refractive index of the liquid crystalline material.
3. Conclusions

The use of replicated structures with a surface relief for use in a switchable beam control device has been studied. Theoretical considerations indicated that when a liquid crystal mixture with refractive indices $n_o=1.5$ and $n_e=1.8$ are used the maximum attainable deflection would be around $40^\circ$. A practical design for broadening of a beam as homogeneously as possible while influencing both polarization directions was devised. The design based on a double cell configuration showed a strong wavelength dependent transmission characteristics and the transmission at 550nm was 70% decreasing rapidly to 50% at 400nm. Due to a production fault direct transmission was higher. Correcting for this we demonstrated that width of a beam of light from a LED source could be increased from 2*6$^\circ$ to 2*22$^\circ$. 