Chiral Liquid Crystal Diffractive Gratings Based on Photoalignment for Application in Augmented Reality Devices

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ABSTRACT

Chiral nematic liquid crystals with a short pitch spontaneously form a helical structure that reflects visible light. By periodic photoalignment, the axis of the helical structure may be tilted. This allows to realize flat optical diffractive gratings or lenses that can be used in augmented reality.

1 Introduction

In augmented reality, images generated by a display are added onto images from the real world. In order to merge these two images, an optical combiner is required. This combiner should ideally preserve the optical quality of both images and have limited loss in brightness.

To maintain a good image of the real world, that is acceptable for the user, the optical combiner should have high transparency and low haze. As the real world is based on the solar spectrum or on illumination systems with a broad spectrum, the optical combiner should be highly transparent for most wavelengths.

The optical combiner and the display can be designed in such a way that light is efficiently transferred from the display to the eye with little losses. Note that an optical combiner has to satisfy the limitations related to étendue, which means that the sum of the efficiencies for coupling from the real world and coupling from the display is at most (in the absence of absorption or scattering) equal to unity:

$$\eta_{world} + \eta_{display} < 1$$

How can efficient coupling from the display be realized, when at the same time, the coupling from the outside world should remain high? We should realize that the efficiencies in the above equation are functions of the wavelength, polarization and angle of incidence of the light. For the angles of incidence, there should be a complete overlap between world and display image. For the wavelength and polarization on the other hand, it is possible to concentrate the emission of the display in narrow intervals where $\eta_{display}$ is high, for example for narrow bands in the red, green and blue range. A small value for η_{world} is not a problem if this occurs in a narrow wavelength interval.

Chiral nematic liquid crystal (CLC) matches the above requirements very well. This material self-organizes into a periodic helical structure with the pitch according to the concentration of a chiral dopant. The material is characterized by two refractive indices: the ordinary and the extra-ordinary refractive indices n_o and n_e respectively. For circularly polarized light with the same handedness as the CLC, incident along the helical axis, a reflection band with high reflectivity appears in the wavelength interval:

$$\lambda \in [n_o p, n_e p]$$

even if the layer has a thickness of only a few μm. Other wavelengths do not strongly interact with the CLC layer and as a result the haze is small.

The second function of the CLC layer is to transform the available angle of incidence into the desired angle of diffraction. Typically the CLC can redirect the light into one particular diffraction angle with high efficiency. The relation between the two angles is determined by the period of the grating Λ and the diffraction equation

$$\frac{2\pi}{\lambda} sin\theta_{out} = \frac{2\pi}{\lambda} sin\theta_{in} \pm \frac{\pi}{\Lambda}$$

By varying the period Λ of the grating over the area of the device, different optical functions can be inscribed in this flat optical device: a linear grating or a custom designed lens.

2 CLC orientation by photoalignment

Nematic liquid crystals are optically anisotropic because the long axes of the molecules are on average parallel to a preferred direction called the director. As a result there is a larger refractive index n_e along the director and a smaller refractive index n_o perpendicular to the director. The CLC is organized in a helical structure, with the director perpendicular to the helical axis, and rotating around this axis. For homogeneously rubbed substrates, the helical axis is perpendicular to the substrates. With photoalignment, the preferred azimuthal angle can vary with the location, and this leads to a tilt in the helical axis in the bulk of the CLC. For a linear grating the period and the tilt angle are constant [1].

Photoalignment can be realized by interference illumination with two coherent beams or by illumination with a beam that is modulated by a spatial light modulator. The first method allows for variations with high resolution, while the second methods allows complete flexibility of the pattern that is to be written on the substrate. For a linear grating, the period is fixed and the helical axis makes a fixed angle with the substrate normal. This concept is illustrated in Fig. 1. For a flat optical device with a more complicated functionality, the helical axis varies with the position on the substrate.

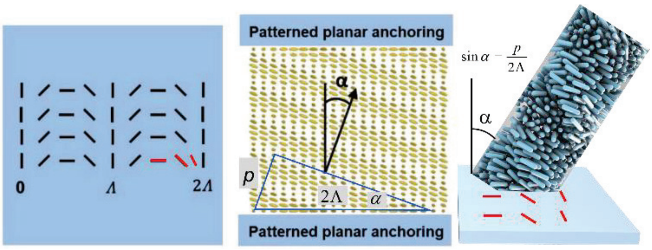

Fig. 1 Photoalignment for CLC with a tilted axis. Left: photoalignment pattern with continuous rotation. Middle: CLC with tilted axis between two substrates. Right: CLC director matching the photoalignment direction.

Linear gratings and CLC lenses with different diameters, periodicities, and optical properties can be realized with different types of liquid crystal. Because of the many degrees of freedom, complicated flat optical devices can be realized.

The principle of photoalignment allows to obtain CLC gratings with a strong tilt of the helical axis, if the period of the photoalignment is small. A tilt angle of 24° has been demonstrated for a period Λ=700 nm and a CLC material with pitch 560 nm [2].

3 Augmented reality devices based on CLCs

Augmented reality devices based on CLC can have excellent properties, thanks to the low haze, good polarization and wavelength selectivity. The optical functionality has to be adjusted to the optical design of the AR device architecture. Two possibilities are illustrated in Figure 2. The first one uses a single semi-transparent flat optical CLC component with complex functionality. The second approach uses a waveguide with two linear gratings: the first one couples light from the display into a waveguide plate, while the second one couples the light towards the pupil of the eye. In both cases the component is transparent for most wavelengths and for the polarization with the opposite handedness.

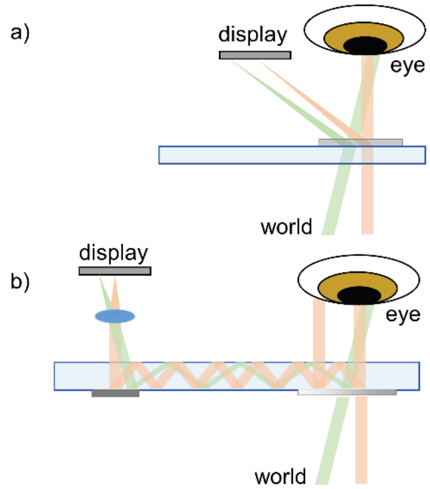

Fig. 2 Two approaches for augmented reality applications based on CLC gratings: a) using one flat optical CLC component, b) using two linear CLC gratings.

4 Conclusions and outlook

CLC flat optical reflective components can be used to realize complicated optical functionalities such as linear diffraction gratings with short pitch and lenses. Different optical components based on CLCs will be demonstrated.

It has been revealed that nematogens with chiral dopants can form structures with even shorter periods. Some materials form blue phase liquid crystal in a certain temperature range, when cooled from the isotropic phase. Recently it has been demonstrated that these materials can be aligned by photoalignment patterns with period below 300 nm [3].

References

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