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To cite this article: Migle Stebryte (2022): Reflective optical components based on chiral liquid crystal for head-up displays, Liquid Crystals Today, DOI: 10.1080/1358314X.2021.2036431

To link to this article: https://doi.org/10.1080/1358314X.2021.2036431

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Published online: 11 Feb 2022.

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Reflective optical components based on chiral liquid crystal for head-up displays

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ABSTRACT

The emerging near-eye displays for see-through augmented reality (AR) and virtual reality (VR) have inspired new applications of optical gratings, for example, as waveguide-coupling components. For such applications, reflective diffraction gratings and reflective lenses based on self-organised chiral liquid crystal (CLC) are strong contenders because of their high diffraction efficiency and unique polarisation selectivity. However, in order to design optical systems that use such components, the optical properties of CLC diffraction gratings need to be thoroughly investigated and understood. In order to better understand the structure and diffraction properties of such components we simulated the behaviour of two cholesteric liquid crystal configurations (planar and slanted) and compared them with experimental results. This paper covers advancements in CLC diffraction grating research, comparison between different theories for the director configuration in the bulk and further investigation of the optical properties of the devices. The evolution of reflective CLC lenses is discussed and lenses with a small f-number are described. In this review paper we show that progress made in the field of CLC-based flat optics has a high potential for AR/VR display systems.

Introduction

Augmented reality (AR) and virtual reality (VR) display systems are emerging technologies promising an immersive experience for the users. While in VR you are fully immersed in a digital content, in AR the digital content is superimposed with the real environment, meaning it needs to have a see-through capability which makes it especially challenging from the optics point of view.

The human eye is a very advanced optical system and has exceptional optical properties such as adaptive focus [1], wide field-of-view (FoV) [2] and high dynamic range [3]. In order to provide a realistic immersive experience these properties need to be matched in an AR/VR system to the highest degree. On top of that, devices need to be lightweight and in case of a wearable – easy to wear. All of these requirements are difficult to achieve using conventional bulk optics.

However, liquid crystal (LC) based flat optics is a strong contender to realise in- and out- coupling elements in the AR/VR applications. For the last two decades there was a lot of research done in a field of a Pancharatnam-Berry nematic LC-based flat optics [4–12]. Such flat lenses and gratings have even been commercialised and are an inexpensive alternative for a traditional glass lenses and conventional diffraction gratings. These components work in transmission and the reported efficiency in a single diffraction order can reach 99% for a certain circular polarisation incident [12]. The smallest reported grating period in these components is about 5 μm and f – numbers >1.6 can be realised. While these are impressive numbers, especially given the relatively cheap and fast fabrication process, there are some limitations that do not allow to achieve smaller f – number and smaller grating periods in nematic LC based components. Flat optics based on chiral liquid crystal (CLC) have drawn a lot of interest especially for the applications of AR/VR display systems, as these components have equally high efficiency and polarisation selectivity. CLC gratings operate in reflection and due to the self-organisation with a small pitch in the CLC phase, a smaller period in the grating can be achieved with this material compared to nematic LC. That also mean efficient diffraction can be obtained into larger angles. Components with a period close to 440 nm and an efficiency of 90% has been reported [13] which confirm a high potential for such components.

However, to implement these components in complicated AR/VR systems a good understanding of the underlying physics is needed. There were several attempts to explain the configuration of the LC director in the bulk when the alignment of the surface is periodically rotating [14–16]. It is important in order to be able to do optical simulations for light propagation in the
structure. There have been several theories to describe the behaviour of the liquid crystal director in the bulk of a CLC grating. The first theory which we call the standing helix model that claims that the director in the bulk has no tilt angle but there is a slant angle that is defined as an angle between the surface and the line where the azimuthal angle is constant [14]. The second theory claims that the director in the bulk is tilted by a constant angle [16]. Recently we have found that the tilt angle of the director is not zero, and also not constant, but it varies as a function of the position. We called this the inclined helix theory and it was later supported by experimental and simulated data [17].

In this review article we will first look into methods to realise flat optics based on CLC, with a focus on the techniques used in the Liquid Crystal and Photonics Group at Ghent University and highlight their advantages and disadvantages. Then we will summarise recent measurements and simulations in this field, particularly, we will look into CLC based diffraction gratings and reflective lenses. The overview focuses on the work at Ghent University, but also work by other groups is discussed.

**Materials and methods**

Chiral liquid crystal is a phase that contains mesogens without mirror symmetry, that tends to self-organise into a periodic helical structure. Due to this periodicity the material has a photonic gap, which depends on the helical pitch and the refractive indices. This property is employed in the flat optics components described in this paper. On one hand, the fact that the material self-organises into a helix means that the layers can be thicker than the period of the rotation at the surface. On the other hand, the photonic bandgap means that the resulting components are reflective for a certain wavelength range which is very interesting for VR and AR applications. They can reflect a circular polarisation that has the same handedness as the helix with a close to 100% efficiency, assuming that the component contains enough layers of half-pitches.

To obtain a CLC mixture with a specific helical pitch in our experiments we use the widely available nematic LC E7 from Merck that has refractive indices $n_o = 1.54$ and $n_e = 1.74$. Then we add a chiral dopant BDH1305 (Merck) and the helical pitch of the resulting mixture depends on the amount of the dopant. This approach gives us the flexibility to choose the reflection band we need.

In order to achieve these promising flat optical components, the chiral liquid crystals have to be arranged in a certain pattern. There are multiple ways to align liquid crystals depending on the desired result, such as microrubbing [18,19], direct laser writing [20,21], nanoimprinting [22–24] and photoalignment [25]. While rubbing is a mature technique and is often used for LC displays, it cannot provide a high resolution. Also, since this is not a contact free technique, there is always a high chance of the contamination of the alignment layer or accumulation of charges [25]. Direct laser writing, even though it can provide high resolution, is very time consuming.

Therefore, the most popular technique to obtain LC based optical components is a contact-free photoalignment. This technique was also used in our work to obtain a periodic variation of the LC director at the substrates (CLC grating) and the lens pattern. The most widely used materials for a photosensitive alignment layer are azo-compounds. The basic principle is based on the cis-trans isomerisation of the azobenzene-groups when illuminated with a linearly polarised UV light. Molecules then orient themselves perpendicularly to the direction of the light polarisation. This orientation is then followed by the LC deposited on top of such layer [25].

There are different ways to modulate the light polarisation in order to achieve a certain pattern on a photoalignment layer. Laser writing has the advantage of a small feature size that is limited by the laser spot size, which is similar to the wavelength of the laser [12,26–28]. Patterns can also be created by using a mask that alters the polarisation or blocks the light [29,30].

The two methods that we use in our group to create a certain pattern on a photoalignment layer are based on a spatial light modulator (SLM) setup [31–35] or on an interference setup [17,36]. In the SLM setup the laser beam is first expanded to match the size of the SLM. Then linearly polarised light is converted to circularly polarised light using a quarter waveplate (QWP) whose optical axis has a 45° angle with the incident polarisation. The propagating beam is then reflected by an SLM which can change a phase of the incident light at each pixel. The reflected light is then converted back to linear polarisation using another QWP. Its optical axis is set at −45° with respect to the laser polarisation direction. The LC in the SLM induces a continuously tunable phase difference between the two linear components of the incoming circular polarisation, which is converted into a continuous modulation of the direction of linear polarisation after passing the second QWP. Since this phase delay can be programmed for each pixel, the SLM setup gives more flexibility and allows achieving an unlimited number of different patterns. However, the resolution of the resulting pattern is limited by the pixel size and diffraction limit which is normally on the scale of a few micrometre.
Meanwhile, in the interference setup, the resolution is limited by the wavelength of the laser used for illumination. The setup to obtain a periodically rotating pattern consists of two coherent, circularly polarised beams that are interfering with each other at a certain angle (see Figure 1(a)). The sum of electric fields of the two laser beams results in approximately linearly polarised light with a polarisation direction that rotates as a function of the position on the substrate with resulting alignment at the surface (Figure 1(a)):

\[ \vec{n}(x, z) = \sin \frac{\pi x}{\Lambda} \vec{1}_x + \cos \frac{\pi x}{\Lambda} \vec{1}_z, \]  

where \( \vec{1}_x \) and \( \vec{1}_z \) are unit vectors along \( x \)- and \( z \)-axis respectively. The period of the grating \( \Lambda \) (rotation of the director over 180°) depends on the wavelength of the light and the angle between the two beams as:

\[ \Lambda = \frac{\lambda}{2 \sin \theta_{UV}}, \]  

with \( \theta_{UV} \) the half-angle between the two beams. This limits the minimal period that can be achieved for the illumination.

In order to obtain a pattern for a lens we use the setup depicted in Figure 1(b). In this case a planar wave is interfering with a spherical wave. In contrast to the setup for the diffraction gratings in this case two beams interfere at 0° or 180° angle. As a result, we get a replica of the lens used to create the spherical wave if the distance between the sample and the lens is equal to two focal lengths (\( 2 f \)). The lens then can be used for the wavelengths that are in the reflection band of the CLC, however the focal length will be inversely proportional to the ratio between the ‘operational’ wavelength and photoalignment wavelength [12]:

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**Figure 1.** Interferometric photoalignment setups for obtaining (a) periodically rotating pattern and (b) lens pattern.
where subscript ‘VIS’ stands for visible light with which the component is used, while ‘UV’ stands for the focal length of the lens and the wavelength used in the illumination setup.

There are two main techniques to make CLC samples: using a cell or spincoating and polymerisation. Here both of these techniques will be discussed. In our research we are mainly using cells which are filled with a liquid crystal after photo-alignment. The fabrication of both type of samples is depicted in Figure 2. First, glass substrates coated with ITO are cleaned in a sonication bath with soap water, acetone and isopropanol. The cleaned substrates are then treated with ozone plasma and a thin layer of the photoalignment material is spin-coated. In our experiments we are using Brilliant Yellow (Sigma Aldrich, 0.5 wt% in dimethylformamide) which is spincoated at 3000 rpm for 30s and soft baked for 5 min at 90°C. Two substrates with a photoalignment material are glued together. The glue contains spacer balls that define the thickness of the cell. This makes it easy to control the thickness of the LC layer in these samples which is an advantage in comparison to spincoating of LC. Another advantage of using a cell configuration for the liquid crystal devices is the possibility to apply a voltage and make an active device. After gluing follows the photoalignment step and finally the cell is filled with liquid crystal at a temperature above the nematic-isotropic phase transition point (for E7 it is 57°C) and then slowly cooled down to the room temperature.

Another approach is spincoating and photopolymerisation of LC. In this case, after spincoating the photoalignment layer, only one substrate is illuminated using a photoalignment step. After that follows spincoating of the mixture containing reactive mesogens, photoinitiator and inhibitor. The layer is then polymerised in vacuum by illuminating it with unpolarised UV light at a temperature below the nematic-isotropic phase transition point, as we want the LC to be in the nematic phase during the photo-polymerisation step [37]. The advantage of this method is that the LC layers are stable after polymerisation. However, spincoating multiple layers is time consuming, more difficult to control the thickness and there is no possibility to have an active component.

**CLC based diffraction gratings and reflective lenses**

Using the techniques described in the previous section one can achieve a variety of flat optical components. Here we will discuss CLC based reflective diffraction gratings and reflective lenses. The optical properties of these components are investigated together with the configuration of the liquid crystal director in the bulk of these structures. In the case of CLC gratings, different models for such configurations are investigated, and the behaviour compared with a planar layer of CLC is discussed. For the CLC lens the optical performance is evaluated and the quality is investigated using polarising optical microscopy (POM). The state-of-the-art of these components among the other groups is reviewed.

**CLC gratings with inclined helical axis**

The intrinsic chiral periodicity of the short pitch CLCs ($p < 2\lambda$) allows the realisation of reflective flat diffraction gratings that are highly efficient and have large

![Figure 2](image-url)

*Figure 2.* The different approaches for fabricating liquid crystal devices: assembling a cell and then filling it with a liquid crystal above the isotropic-nematic phase transition temperature (top) and spincoating and photopolymerising the LC on top of a photoaligned substrate (bottom).
diffraction angles. This can be achieved by creating a periodically rotating pattern at the surface of the substrate which is then followed by the deposition of a layer of CLC on top. The linear increase of the rotation angle allows to control the direction of the reflected wavefront [38]. As previously mentioned, this can be achieved by using the interference setup depicted in Figure 1(a) and the resulting component reflects light at the angle, defined by grating equation:

\[ n_{\text{out}} \sin \theta_{\text{out}} = \frac{m \lambda}{\Lambda} + n_{\text{in}} \sin \theta_{\text{in}}, \]

where \( m \) is an integer number indicating the diffraction order, \( \Lambda \) is the alignment period (indicating a rotation of 180°) and \( \lambda \) is the wavelength of the incident light. In case a circularly polarised light is incident and the handedness is the same as the helicity of the CLC, almost all the reflected light is coupled into the 1st diffraction order \((m = 1)\). We have recently shown, using numerical director configuration simulations, that the periodic pattern defined at the surface induces a tilt in the bulk of such structure and the helical axis is inclined relatively to a surface normal (see Figure 3(a)). This tilt varies along the y-axis. Components having a diffraction efficiency to the 1st order of 88% was also fabricated and measured [36]. In this particular case part of the light (8%) is lost due to the reflections from the glass substrate, therefore the efficiency could be easily improved if needed by applying an anti-reflection coating. The measurements were compared with optical simulations in which we used dielectric constant values calculated using the results from director configuration simulations and a good correspondence was found. Using this model as a reference point we derived an analytical formula for the azimuthal and polar angles in such structure. These angles as a function of coordinates can be expressed using a spherical trigonometry (see Figure 3(b)) [17]:

\[
\begin{align*}
\cos \theta &= \sin \alpha \sin A \\
\cos \varphi &= \frac{\cos A}{\sin \sigma},
\end{align*}
\]

here \( A = \frac{2\pi}{p}(x \sin \alpha + y \cos \alpha) \) with \( p \) a helical pitch of the CLC.

**Figure 3.** (a) Schematics of CLC grating with inclined helix, here \( \alpha \) is the inclination angle of the helical axis, \( p \) is the helical pitch of the CLC, \( \theta_{\text{in}} \) is the AOI with respect to surface normal, \( \theta_{\text{out}} \) is the AOI with respect to the helical axis, \( d \) is the thickness of the CLC layer and \( s \) the number of half-pitches, red arrows indicate the pattern of photo-alignment at the surfaces; (b) schematics of LC director angle definition in spherical coordinate system. Here \( \varphi \) and \( \theta \) are, respectively, the azimuthal and polar angle, \( A \) is the angle of LC director with respect to the z axis; (c) schematics of CLC grating with vertical helix; (d) schematics of planar CLC layer. In the coordinate system used in this work x-z is the sample plane and y-axis is the substrate normal [17].
Some other previous theories were claiming that the helix is actually standing and there is no tilt in the director [14,15] or that the tilt angle is constant [16]. However, by using numerical simulations and comparing them with the measurement results we proved that the inclined helix theory is the right one [17].

For the simulations we defined three different models: inclined helix, standing helix and planar CLC. In the inclined helix model, we use analytical formulas for the director configuration in the bulk of the diffraction grating shown in Equation (5). For the standing helix model the tilt angle was set to 0° while the azimuthal angle was expressed as \( \varphi' = \frac{2\pi}{\Lambda} (x + y \cot \alpha) \) (see Figure 3(c)). Finally, in the planar CLC layer we assume that at the surface, the director is oriented in the same direction, the tilt angle is set to 0° and the azimuthal angle varies only as a function of \( y \): \( \varphi'' = \frac{2\pi}{\Lambda} y \) (see Figure 3(d)).

For the optical simulations we use software COMSOL Multiphysics 5.5, where we implemented the models mentioned before. The software allows calculating the diffraction efficiency of different orders as a function of wavelength. We simulated transmission spectra for 5 different angles of incidence \( \theta_{in} \): 0°, 7°, 14°, 21° and 27°. All of the AOs are in glass. We simulated a structure that has a period of 700 nm, helical pitch of 560 nm and thickness of 5.5 μm. Further details of the model can be found in [17]. The same parameters where used in the sample we fabricated, and we measured the transmission spectra and compared them with simulation results.

We simulated transmission spectra for 6 different incident polarisation states: TE, TM, -45°, 45°, right-handed circularly polarised (RHCP) and left-handed circularly polarised (LHCP). Since the helical axis is inclined in a CLC grating, we introduced the angle of incidence (AOI) with respect to the helical axis \( \theta_h \) so that we could compare the properties of the grating with those of the planar CLC layer with light incident at a certain angle. Hence, in the case of grating this angle was equal to AOI + inclination (or slant angle in case of the standing helix model) as can be seen in Figure 3. We first made a comparison of measured of inclined helix spectra and simulations for the inclined helix and the standing helix theories, when the incident light has TE polarisation. As can be seen in Figure 4 the measurement result fits much better with our inclined helix theory. Interestingly, for the \( \theta_h \) larger than 31° (\( \theta_{in} = 7° \) in glass) the transmission drops below 50% in the measured and simulated inclined helix spectra, while in the standing helix model it stays around 50%. This effect can be explained by an appearing full reflection band which is characteristic for a planar CLC with a light incident at large AOs. In this case the angle of inclination of the helical axis is set to 24°. This phenomena in planar CLC has been discussed in the literature [39]. The colour of the CLC layer was changed electrically, inducing a uniform laying helix and also by rotating the sample. In order to observe a full reflection band, the AOI had to be at least 45° which is not always practical in applications. If we assume that the helix is standing, then the AOI of 7° (without slanted angle added) is not sufficient to start observing this effect. However, as we can see from the experiment, in a sample it can be observed with the same AOs as in the simulations for the inclined helix model. Therefore, it is obvious that the inclined helix theory is the correct one and the following simulations are based on this theory and compared to experimental results.

Simulations for the different polarisation states gave interesting results but the most evident are the ones for the two circular polarisations (Figure 5). As expected, for the RHCP light, the transmission is close to 0% in the reflection band while for the LHCP light it is close to 100%. However, near \( \theta_{in} = 45° \) we can see a dip in transmission in all three cases for the LHCP light. While the transmission continues to decrease in the case of planar CLC, it goes back to 100% in the measured and simulated inclined helix spectra as we go to a larger AOI. Both experimentally and in the simulation for a CLC grating.

![Figure 4](image-url)

Figure 4. (a) Measured transmission spectra of CLC grating with \( \Lambda = 700 \) nm for TE polarisation for different angles with respect to the helical axis \( \theta_h \). Numerically calculated transmission spectra for TE polarisation for different angles \( \theta_h \) assuming inclined helix (b) and vertical helix (c) models [17].
with inclined helix we can see a narrowing of transmission spectra for the RHCP. To investigate this further and find the reason of such narrowing we ran simulations with a Gaussian beam which showed, that in case of the CLC grating with an inclined helix, light gets coupled into the CLC layer and then is outcoupled in the forward direction.

**Figure 5.** Transmission spectra for right- and left-handed circular polarisation for different angles $\theta_H$: (a) experimental; (b) simulated for CLC grating with inclined helix and (c) simulated for planar CLC layer [17].

**Figure 6.** (a) Numerically calculated transmission spectra with linearly $-45^\circ (-1 0 1)$ polarised light at $\theta_m = 21^\circ$ for a CLC grating with a $24^\circ$ inclined helix ($\theta_H = 45^\circ$), and for a planar CLC with $\theta_m = \theta_H = 45^\circ$. Simulated field intensity distribution for a linearly $-45^\circ (-1 0 1)$ polarised Gaussian beam with wavelength (b) $\lambda = 646$ nm and (c) $\lambda = 700$ nm incident on the CLC grating at an angle $\theta_m = 21^\circ$ ($\theta_H = 45^\circ$) [17].
direction with a lateral shift (see Figure 6). This can be explained by looking at the grating Equation (4): there exists a cut-off wavelength at which \( \sin \theta_{\text{out}} \) becomes equal to 1 and as we go to larger wavelengths, light cannot be diffracted back because of total internal reflection, and it is coupled forward instead. The cut-off wavelength can be calculated from the grating equation;

\[
\lambda_{\text{cut-off}} = (1 - \sin \theta_{\text{in}}) n_{\text{glass}} \Lambda
\]

(6)

This formula is important to take into account when designing components that need large AOIs, but also for lenses that consist of concentric diffraction gratings with a radially varying period, because it can limit the reflection bandwidth of the component.

**CLC based reflective lenses with a small f-number**

The first reflective CLC based lenses were fabricated already in 2016, using an exposure system comprising a liquid crystal display projector and a rotatable wave-plate to create orientation patterns based on photoalignment. However, they had a radius of only 0.5 mm and focal length of \( f = 20.3 \text{ cm} \) [39]. The next development was achieved in 2020 by Wu [40] when they fabricated lenses using a commercially available transmissive Pancharatnam-Berry lens (PBL) as a master lens. Lenses having a diameter of 2.45 cm and \( f - \text{number} > 0.3 \) were achieved. A spincoating and photopolymerisation technique was used to deliver a LC layer in this case. While it was an impressive achievement, the range of parameters (especially focal length) of lenses fabricated in this way is limited by the available PBLs.

We used a different approach using an interference setup. In our case we interfere a plane wave with a spherical wave and achieve a parabolic pattern that after a deposition of CLC results in a reflective flat lens. An interference setup that can be used to achieve it is depicted in Figure 1(b). The properties of such lenses depend on the lens used to create a spherical wave. It defines the focal length of the resulting lens and the beam diameter defines the size of the reflective CLC lens. This gives additional flexibility as there is a wide variety of conventional lenses with different focal lengths available. We also used a cell approach which makes the process faster and the control of the CLC layer easier.

To achieve a small \( f \)-number aspheric lenses with a small focal length and a microscope objective with a high magnification was used. We fabricated lenses with a \( f \)-number as small as 0.4 (Figure 7). Such components are very efficient with lensing efficiency close to 90% for a right-handed circular polarisation incident. Size of the lenses on each sample is around 2–3 mm and focal length varies from 1–2 mm (see Table 1). Once again, the efficiency can be improved by applying an anti-reflective coating as 8% were lost due to the Fresnel reflections from the glass substrates.

The microscope image depicts the colour change as we go to the sides of the component (Sample 2). It is an indication that the period becomes smaller as we go further from the centre since the helical axis gets more inclined and the reflection spectrum is blue shifted as explained in the previous section. The period at the edge of the sample was measured and it is around 1 \( \mu \text{m} \). That corresponds to an \( f \)-number of 0.6 using a following equation for a lens designed for \( \lambda = 633 \text{ nm} \) [41]:

![Figure 7](image-url)

**Figure 7.** (a) A photo of a cell with 3 CLC lenses (samples 1, 2 and 3 in Table 1); (b–d) POM image of a lens in reflection between parallel polarisers going from the centre towards the edge of the lens; (e–h) POM images of a lens in reflection between crossed polarisers going from the centre towards the edge of the lens.
Table 1. Diameter, focal length and f-number measurement results for the CLC-based reflective lens samples.

| Sample | Diameter, mm | Focal length, mm | f-number |
|--------|--------------|-----------------|----------|
| 1      | 3.5          | 4               | 1.1      |
| 2      | 3.5          | 1.6             | 0.46     |
| 3      | 3.5          | 2.8             | 0.8      |

\[ f - \text{number} = \frac{1}{2 \tan\left(\sin^{-1}\frac{\lambda}{\Lambda_{\text{min}}}\right)} \]  

where \( \lambda \) is a wavelength for which the lens is designed and \( \Lambda_{\text{min}} \) is a minimum period required to obtain such f-number. As mentioned before periods as small as 440 nm have been reported in CLC based diffraction gratings [13]. Therefore, we can go to a very small f-numbers using this technique. The main limitation in the CLC lenses with a large numerical aperture is the bandwidth as the reflection band shifts towards the shorter wavelengths as the period decreases. This means that if the f-number is very small the wavelengths reflected in the centre of the lens might be transmitted close to the edges of the component (as they will be outside of the reflection band in that region). To estimate the shift across the lens models for the director configuration and optical simulations described in the previous section come in handy.

Conclusion

CLC-based gratings and reflective lenses promise a possible solution for current problems in AR and VR systems with large diffraction angles allowing wider FoV, and efficiency and polarisation selectivity of the components reducing the energy requirements for the displays of such systems. On top of that, both lenses and gratings can be obtain using a simple and inexpensive fabrication method. In order to make use of these properties, a good understanding in the physics behind them is needed. In this review we gave an overview on different models describing the structure of these components. Comparison or experiments and optical simulations showed that inclined helix model is the best to describe the azimuthal and polar angles in CLC diffraction gratings. With a help of this model polarisation and diffractive properties were investigated. Some interesting phenomena were described such as a cut-off wavelength and forward diffraction in CLC gratings which are important when designing systems comprising gratings and lenses and estimating a bandwidth. A full reflection band observed in such gratings at smaller AOIs than in a planar CLC can also have a potential application. Reflective CLC lenses with f-number <0.5 is possible to achieve using this technique and the efficiency of such flat lenses is close to 90%. These recent advances in the flat optics based on CLC enables implementation of these simple components into a complicated AR/VR display systems. Even though a further improvement and optimisation in the design and fabrication method is needed, systems containing reflective CLC gratings and lenses are very likely to be commercially available in a near future.

Acknowledgements

The author would like to thank Prof. Kristiaan Neyts for the guidance and help with this paper. The author is also very grateful to the colleagues from LCP Group at Ghent University that helped her with her research: Prof. Jeroen Beeckman, Dr. Inge Nys and Yera Ye. Ussembayev.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was funded by the Research Foundation—Flanders, grant number 1588220N.

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