

Efficient Large-Angle Diffraction using Patterned Chiral Liquid Crystal

Kristiaan Neyts^{*,*****}, Migle Stebryte^{***}, Rohan Sharma^{*,*****}, Xu Ke^{*,**}, Pouya Nosratkhan^{*,**}, Le Zhou^{*,**}, Inge Nys^{***}

^{*}Hong Kong University of Science and Technology, ECE Department, Clear Water Bay, Hong Kong, SAR

^{**}State Key Laboratory of Advanced Displays and Optoelectronics Technologies, HKUST, Hong Kong, SAR

^{***}Liquid Crystals and Photonics Group, ELIS Department, Ghent University, Ghent, Belgium
eeneys@ust.hk

Abstract

Chiral liquid crystals spontaneously arrange into a helical structure of which the pitch depends on the concentration of the chiral dopant. If the effective wavelength inside the liquid crystal matches the period of the helix, Bragg reflection occurs and light is efficiently reflected. A periodic photoalignment pattern at the surface of a substrate can be used to tilt the axis of the helical structure and redirect the reflected light into a desired direction. This principle is used in waveguide-based beam combiners for augmented reality devices and in single component spectrometers.

Author Keywords

Chiral liquid crystal; photonic band gap; diffractive grating; augmented reality; geometric phase grating.

1. Introduction

Thin diffractive optical elements (DOE) use small-scale variations in the refractive index to diffract incident light. The principle is different from traditional optical elements, which are based on refraction or reflection of light. There are different approaches to realize DOEs. Relief grating DOEs consist of a layer, typically with a high refractive index, that has a three-dimensional structure, in contact with air or with a low-refractive-index material. Another type of DOE uses a layer of homogeneous thickness of a material in which the refractive index is modulated in space. Such DOEs can be based on photosensitive materials that have been illuminated by an interference pattern. The illumination can increase or decrease the refractive index or make the refractive index complex.

In this work we use DOEs that are based on nematic liquid crystal. The thickness of the layer is homogeneous and the ordinary and extra-ordinary refractive indices of the material remain the same. The modulation of the dielectric tensor is induced by the three-dimensional orientation of the liquid crystal director, the average orientation of the long molecular axis. For nematic liquid crystals the difference between the ordinary and extra-ordinary refractive index is typically between 0.1 and 0.4. To achieve an effective reflective grating in a sub-micrometer layer, this difference is too small, however, repeated modulation of the director orientation can increase the reflectivity to close to 100%.

Achieving a DOE with large diffraction angles is linked to rapid variations in the direction parallel to the substrate surface. If a diffractive structure with period Λ is illuminated with light perpendicular to the substrate, then the diffraction angle θ for the m^{th} order for wavelength λ is determined by $\sin\theta = m\lambda/\Lambda$. The alignment at the surface of a liquid crystal cell can be determined by photoalignment. A process in which patterned linearly polarized UV or blue light is incident on a photosensitive material, for example a material containing azo-dyes. For transmissive diffractive nematic liquid crystal gratings, a high

efficiency is obtained when the thickness of the layer corresponds to a half wave plate (retardation π between the two eigenmodes), but a small period Λ requires a fast variation of the azimuthal angle of the director, and large splay and bend energies. Therefore, it is difficult to increase the diffraction angle above 10° for visible light diffracted on a nematic liquid crystal layer [1].

Chiral liquid crystal (CLC) with a short intrinsic pitch can easily achieve rapid variations in space with limited elastic energy, because the twist is linked to the chiral asymmetry of the molecular structure. Therefore they are well placed to achieve large diffraction angles with high efficiency.

2. CLC properties

In a CLC, the dielectric tensor is modulated periodically in the direction of the helical axis and the eigenmodes of propagation are superpositions of forward and backward propagating plane waves. For some frequencies and directions of the wave vector, propagation of light is not allowed, and the dispersion diagram shows a photonic band gap. When incident photons have properties corresponding to the band gap, they are effectively reflected, with a penetration depth of only a few micrometer. For light incident along the helical axis, only one circular polarization is reflected, namely the one with the handedness identical to that of the helical structure. When light is incident under an angle, there is a wavelength range where both polarizations are reflected, and a so-called full band-gap is created. Fig.1 illustrates the angle dependency of the reflection spectrum and the corresponding k-vector diagram with the photonic bandgap.

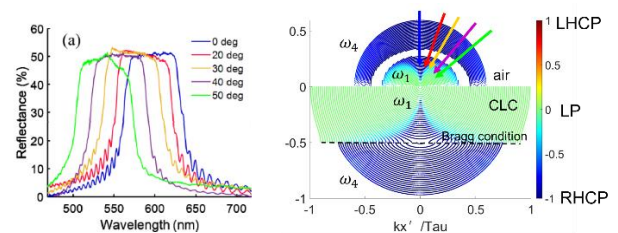


Figure 1. Angle-dependent reflection spectrum and corresponding k-vector diagram in air and in the CLC.

3. CLC Diffraction Gratings

Linear CLC gratings can be fabricated by using substrates with periodic photoalignment [2]. Typically the pattern is achieved by illuminating photosensitive alignment layers containing azo-groups with two interfering plane waves with circular polarization. This leads to a linear increase of the azimuthal angle of the incident electric field. If the two beams make an angle θ with the substrate normal, then the resulting LC grating has a period $\Lambda = \lambda / (2 \cdot \sin\theta)$. The chiral liquid crystal with pitch p can adjust to this boundary condition by tilting the helical axis over an angle α according to $\sin\alpha = p / (2\Lambda)$. The condition for Bragg

reflection and the photonic band gap are then tilted accordingly, as illustrated in Fig. 2.

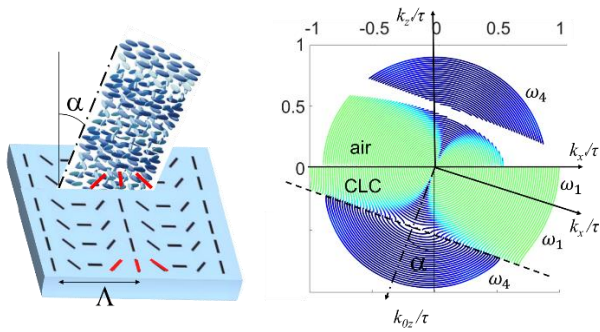


Figure 2. CLC with tilted helical axis on a substrate with patterned alignment (left). Diagram with the k-vector in the CLC and in air for a layer with tilted helical axis (right).

CLC reflective gratings with a tilt can realize high reflectivity (>95%); diffraction occurs predominantly in a single order (>95%); the diffraction angle can be more than 45° in a glass substrate (sufficient for total internal reflection) and there is limited scattering. These components are very well suited for beam combiners in augmented reality, because they effectively reflect light when the conditions meet the photonic band gap, while other wavelengths are well transmitted [3]. Note that in the CLC with a tilted helical axis, the director in the bulk rotates while remaining perpendicular to the helical axis and not parallel to the substrates [4,5].

When incident light satisfies the condition for the bandgap, effective reflection occurs. For a single layer of CLC, the reflective properties at both sides may be different, when the alignment patterns at both sides are not the same. To illustrate this, a device has been fabricated with two substrates with different periodicity: the substrate at the right side has a variation in the vertical direction and the substrate at the left side has a variation in the horizontal direction, as illustrated in Fig. 3. Right handed circularly polarized (RHCP) light entering from the right is diffracted in the vertical plane, while RHCP light from the left is diffracted in the horizontal plane. In this case the helical structure of the CLC has a different tilt at both sides of the device. One might expect that the mismatch in tilt of the helical axis would lead to a lot of disorder and lots of disclination lines. A careful study based on experiments with larger pitch CLC and numerical simulations has shown that this is not the case [6]. In the middle of the layer, the director may tilt towards the vertical direction to realize a disclination-free configuration.

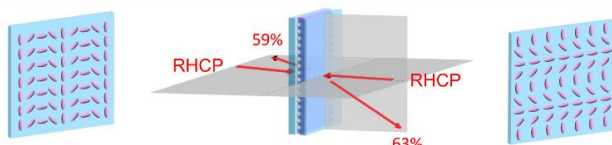


Figure 3. CLC layer embedded between two substrates with different photoalignment patterns. The diffraction at both sides occurs according to the periodicity at the substrate and the two parts of the layer are optically shielded from each other. The CLC can form a continuous director pattern, without disclinations.

Diffraction in CLCs is based on distributed Bragg reflection in a

periodic structure and the reflective mode is conceptually the most logical one. However, it is also possible to design optical elements that operate in transmission, by combining the CLC reflection with total internal reflection if the CLC is adjacent to a material with low refractive index such as air. Fig. 4 illustrates the propagation of a light beam incident from the air side, entering the CLC layer with a tilted helical axis. Light is reflected two times: first by the CLC, then by the interface with air due to total internal reflection. Finally the beam is transmitted through the CLC at an angle that is not within the photonic band gap. The experimentally measured efficiency for this complicated procedure is over 85% [7].

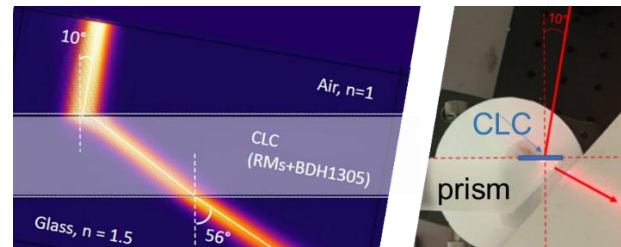


Figure 4. Simulated light propagation for a CLC layer with tilted helical axis at the interface between air and a glass substrate (left). Experimental setup to measure the diffraction in the CLC component, mounted on a prism with a 45° wedge (right).

4. CLC Spectrometers

To illustrate the versatility of CLC diffractive optical elements, we have designed and fabricated single component spectrometers with two different approaches. In the first approach, a thin flat CLC layer is deposited on a photoalignment layer that has been patterned by the interference illumination of two coherent spherical laser beams. The periodicity of the grating varies over the surface of the substrate and the CLC in contact with the photoalignment layer obtains a tilt direction that depends on the position of the substrate [8].

The principle of this spectrometer is illustrated in Fig. 5 together with three images of the slit on the screen for narrow band red, green and blue light.

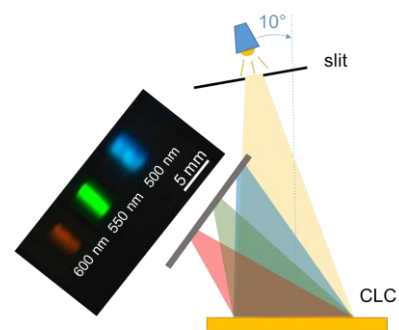


Figure 5. Spectrometer consisting of a single CLC layer obtained from interference illumination with two spherical laser beams. Light from the entrance slit is diffracted and focused onto a screen.

A second approach for a single component spectrometer uses a curved substrate to realize the focusing functionality, while the diffraction is realized by a linear grating. The linear grating is achieved by photoalignment using two interfering plane waves. The technology is implemented on a spherical substrate with diameter 30 mm and radius of curvature 100 mm. The processing

steps to realize the grating on a curved substrate are illustrated in Fig. 6. Instead of using a CLC between two substrates, the DOE is realized by spin coating a layer of polymerizable CLC on the curved substrate and afterwards fixing the director orientation by polymerization under influence of UV light. The photographs at the bottom show the reflection of a fluorescent tube light on the curved substrate. The grating on the left is strongly reflecting green light, while the grating on the right is mainly reflecting yellow light [9].

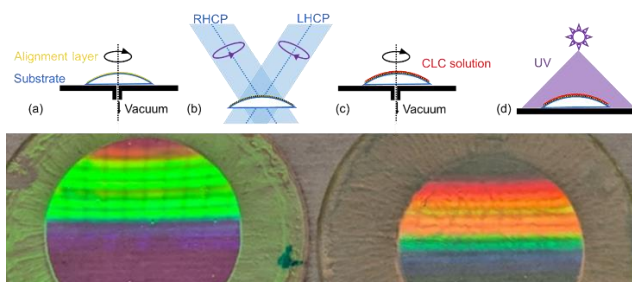


Figure 6. Fabrication steps to realize a polymerized reflective CLC grating on a curved substrate: (a) spin coating the photoalignment layer; (b) holographic illumination; (c) spin coating CLC; (d) photopolymerization of the CLC layer (top). Image of two curved substrates with different CLC layers, reflecting light from a fluorescent tube lamp (bottom).

5. Conclusion

With CLC layers deposited on a substrate coated with a photoalignment layer, interesting diffractive components can be realized: linear gratings, gratings with lens functionality and transmissive gratings. The optical quality of the resulting CLC DOEs is high with efficient diffraction into a single order, when the incident light has parameters that correspond to the forbidden band gap of the CLC layer. The fabrication process is relatively simple and involves only spin coating, interference illumination and CLC layer deposition. Gratings with sub-micrometer period can easily be obtained and the period (and the CLC tilt angle) can be varied over the substrate. The technology can be expanded to large substrates and the substrates can be curved.

6. Impact

The results demonstrate that CLC layers can be used as diffractive optical elements with the following characteristics:

- Highly efficient single order diffraction for one polarization;
- Large angle diffraction is possible, compatible with total internal reflection into a planar waveguide;
- Diffractive gratings can be deposited on curved substrates and be polymerized;
- Diffractive gratings can include the functionality of a lens and focus the light;
- A single layer of CLC may have different reflective diffractive properties when illuminated from opposite sides;

- Large angle diffraction in the forward direction is also possible.

The large number of examples and the high quality of the devices indicate that this approach can be successfully used in many kinds of display applications to replace conventional bulk optical components. Diffractive CLC components are particularly useful when the light source emits a narrow wavelength range, when the light is polarized and/or the light is more or less collimated, which is the case in many display technologies based on LEDs, μ LEDs, LCDs or DMDs. The advantage is that the layers are only a few micrometer thick, which is an important advantage for AR or VR devices where the weight must be kept as low as possible.

7. Acknowledgements

The authors acknowledge funding from the Research Foundation Flanders (FWO), Grants G0C2121N, 1S13623N, and project 1257423N.

8. References

1. Nys I., S. Liu, Y.-N. Huang, O. Strz̄ysz, P. Kula, K. Neyts, Geometric Phase Flat Optical Gratings with High Diffraction Angle Based on Dual-Frequency Nematic Liquid Crystal. *Adv. Optical Mater.* 2023, 11, 2300972.
2. Chigrinov, V. G.; Kozenkov, V. M.; Kwok, H.-S. *Photoalignment of Liquid Crystalline Materials: Physics and Applications*; Wiley: Hoboken, NJ, 2008.
3. Nys, I.; Stebryte, M.; Ussembayev, Y. Y.; Beeckman, J.; Neyts, K., Tilted Chiral Liquid Crystal Gratings for Efficient Large-Angle Diffraction. *Adv. Opt. Mater.* 2019, 7 (22), 1901364.
4. Stebryte, M.; Nys, I.; Ussembayev, Y. Y.; Beeckman, J.; Neyts, K. Large angle forward diffraction by chiral liquid crystal gratings with inclined helical axis. *Crystals* 2020, 10, 807.
5. Yun-Han Lee, Ziqian He, and Shin-Tson Wu, "Optical properties of reflective liquid crystal polarization volume gratings," *J. Opt. Soc. Am. B* **36**, D9-D12 (2019)
6. Stebryte M., Nys I., Beeckman J., Neyts K., Reflective 2D diffraction grating based on short pitch chiral liquid crystal, *Journal of Molecular Liquids*, Volume 394, 2024, 123734.
7. Stebryte M. , Inge Nys, Jeroen Beeckman, and Kristiaan Neyts Single Order Diffraction at a Negative Angle Based on a Chiral Liquid Crystal with an Inclined Helix, *ACS Applied Optical Materials* 2024 2 (10), 2067-2074
8. Stebryte, M.; Nys, I.; Beeckman, J.; Neyts, K. Chiral Liquid Crystal Based Holographic Reflective Lens for Spectral Detection. *Opt. Express* 2022, 30 (24), 42829.
9. Sharma R., Migle Stebryte, Brecht Berteloot, Inge Nys, and Kristiaan Neyts, Chiral Liquid-Crystal-Based Concave Holographic Spectrometer on a Curved Substrate, *ACS Applied Materials & Interfaces* 2024 16 (32), 42957-42965