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Modeling of Cholesteric Liquid Crystal layers for a Luminescent Solar Concentrator

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Abstract: This report is about an internship which was part of a project that aims to develop a Luminescent Solar Concentrator (LSC) for commercial use. In the design of the LSC a wavelength selective mirror is used, in this case in the form of a Cholesteric Liquid Crystal (CLC) layer. The usage of this filter increases the efficiency of the system. To optimize the design of the LSC, a computer program has been adapted to simulate the behavior of the CLC. The calculations match the experiment and can be used to predict the Stokes parameters of the reflected and the transmitted light. The results have been used to make design decisions for the CLC.

Conclusions: We have two options for wavelength-selective filters that can be used for LSCs, which have been investigated both theoretically and experimentally. One is a combination of right- and left-handed gradient-pitch CLCs, the other is a combination of two right-handed gradient-pitch CLCs with a half-wave plate in between. In both cases a good agreement between calculations and experiments has been found. These wavelength-selective filters are suitable to be combined with a phosphor that has a broad absorption spectrum and a narrow emission spectrum, as is being developed in our project.
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Chapter 1

Introduction

As climate change is becoming a bigger problem globally alternative sources of energy, replacing oil, coals and gas, become more of a concern. Although nuclear (fission) energy is a clean and quite safe source of energy, the nuclear waste it produces and the concerns of people regarding the safety remain an issue. Another promising source of energy is nuclear fusion. It has been possible to generate and observe fusion reactions for a long time now, but the problem has been, and still is, to get more energy out than is put in. Whereas it will take some time (and maybe forever) until nuclear fusion becomes available as a conventional source of energy, we have other sources of sustainable energy available at this moment. The most common types of those are wind and solar energy.

For economic operation of wind power, all the available output of energy must be taken when it is available. This is not a problem if wind power comprises only a small part of the overall energy supply. The same counts for solar energy. The amount of solar energy reaching the surface of the earth is so big that in one year, the total energy reaching the surface is twice as much as the total obtainable energy from all non-renewable sources [1]. This, and the fact that it is totally clean, make solar energy interesting as a renewable energy source.

Nevertheless, attaining high enough conversion efficiencies at low costs is still a problem in photovoltaics (PV) research, as it has been for decades. The current prices of PV modules are too high and the widespread usage of solar energy still needs financial support schemes. To reach a lower cost per installed capacity, several routes are being pursued, most of those focussing on the better usage of the complete solar spectrum, for example with the use of tandems. These are stacks of solar cells, each operating in different ranges of wavelengths.

Another approach is to concentrate the light. This is what is done in a Luminescent Solar Concentrator (LSC). The LSC is an old idea, which was first suggested in 1973 [2]. Back then, efficiencies were not good enough to commercialize, but in recent years interest in LSC has seen a revival. It is mainly because of advances in material science and a better theoretical understanding of the physical phenomena that researchers are now more confident it will be possible to make cost-effective LSCs [2]. Philips has a special interest in LSCs because it thinks it has the technology and the expertise to really make it work this time.

1.1 Solar Cells

A solar cell uses light-absorbing materials to generate what is called an electron-hole pair under illumination. The solar cell consists of P-type and N-type material. These materials are specifically tailored to conduct negative and positive charges, as N-type material conducts electrons
well and P-type material conducts positive charges in the form of electron-holes. These materials are both made from a semiconductor like Si and then modified by adding a dopant. For the N-type material an atom, for example a phosphorous atom in the case of Si, is introduced that contributes an extra electron to the structure when it is incorporated. For the P-type an atom is added that has one electron less than Si, such as a boron atom. This will create a positive hole. The P-material and the N-material are stacked. The interface between these materials is called the P-N junction and the device will act as a diode and as a solar cell. A schematic depiction of a solar cell is given in figure 1.1. In this figure it can be seen that the incoming photons can be reflected back or can be absorbed in the PV cell, generating a current in the attached light bulb. When looking at the energy levels during this process, the situation can be represented by figure 1.2. In this case before the photons comes in the valence band of the material is almost totally filled (as it is in semiconductors). An incoming photon then excites an electron from the valence band to the conduction band. The difference between these energy levels is called the bandgap. For Si this bandgap is 1.1eV, which corresponds to photons with a wavelength of 1100nm, so if light with wavelengths shorter than 1100nm enters a thick Si wafer, it is absorbed. This produces an electron in the conduction band and it leaves a hole in the valence band. Because the P-N junction acts as a diode, charge can only flow one way and for the electron and the hole to recombine, charge flows through the attached wire, thus generating an electrical current [3].

1.2 Luminescent Solar Concentrators

1.2.1 Introduction and history

The idea of the Luminescent Solar Concentrator is to use a luminescent material embedded in a lightguide to collect sunlight and guide it to a photovoltaic cell (PV). The advantage of this method is that this type of concentrator is the only concentrator known that can achieve high values of concentration without tracking as opposed to concentrators based on geometric optics.
Figure 1.2: This energy-band diagram of a P-N junction solar cell shows the generation and transport of charge carriers.

Moreover it doesn’t need direct sunlight, but can be used without problem in diffuse sunlight and is well adapted to overcast conditions that occur frequently in temperate climates [4]. The principle of fluorescence light trapping inside a medium of higher index refraction is quite old [4]. It was used since the early 1950s in atomic physics, but it was not until the energy crisis of the 1970s that the suggestion to use this principle for concentration and conversion of solar energy was made [2]. Since then, a lot of research has been done on LSC’s, and although not successful in large scale power production up to now, the research has catalyzed a number of research areas such as the development of optics and thermodynamics of fluorescent dyes with previously unknown photostabilities, a much deeper understanding of the optics and thermodynamics of fluorescence emission and the incorporation of organic dyes in inorganic glass materials [2].

However, the efficiencies and the photostability of the dye were not good enough for commercialization [2]. Recent results in material science (see for example section 1.2.5) as well as theoretical advances make it more likely that these problems of the past will be overcome.

1.2.2 General Principle

A schematic drawing of a LSC is shown in figure 1.3. The sunlight is incident on the top of the material, while the sides and the bottom are covered with mirrors, save for one side, which is reserved for the PV cell. The concentrator is made of a transparent material, doped with a luminescent dye. The incoming light is absorbed in the absorption spectrum of the dye and emitted in the emission spectrum of the dye, which is shifted to the red. A basic requirement for efficient collection for the incident wavelength to have a short absorption length and for the emitted wavelength to have a long absorption length. This can be done by using a phosphor or dye with absorption and emission spectra that are well separated [4]. In general the emission is isotropical and is subjected to refraction upon reaching the interface.
Figure 1.3: Schematic depiction of the LSC, showing possible processes. The solid blue lines indicate incident light, the dashed lines indicate emitted light, the black dots indicate parasitic absorption by the polymer or mirror and the rectangles indicate an absorption by the luminescent material. Process 1 represents a lightbeam that is not absorbed and is reflected by the mirror. Process 2 represents a photon that is absorbed in the mirror. Process 3 represents a photon that is parasitically absorbed by the polymer. Process 4 represents a photon that is absorbed by a dye molecule and not emitted due to a quantum efficiency of the luminescent material lower than 100%. Process 5 represents absorption and emission by a dye molecule followed by parasitic absorption by the polymer. Process 6 represents absorption by a dye molecule and emission in the escape cone. Process 7 represents absorption and emission by a dye molecule followed by parasitic absorption in the mirror. Process 8 represents absorption and emission by a dye molecule followed by reabsorption by another dye molecule, whereafter the photon is emitted in the escape cone. Process 9 represents absorption and emission by a dye molecule, followed by total internal reflection and absorption in the PV cell; the desired process [5].
between the slab and air [2,6]. Most of the light is trapped inside the collector plate due to the
laws of refraction and is transmitted to the edges of the plate via total internal reflection where it
is converted to electricity by a PV cell, while another part is emitted under an angle that doesn’t
allow internal reflection. The edge area of the plate where the light comes out is much smaller
than the light absorbing area, so the plate acts as a concentrator [2].
The light that is not totally internally reflected is said to be in the escape cone and it is transmitted
out of the LSC, so it doesn’t reach the PV cell and it is lost. Emission in the escape cone is one
of the major loss mechanisms of LSC’s as about 25% of the dye emission is typically lost in this
way (process 6 of figure 1.3 [7]). Additional losses are caused by reabsorption and re-emission
in the escape cone (process 8 in figure 1.3). It is therefore interesting to do research on this topic.
Other loss mechanisms are depicted in figure 1.3.

1.2.3 The Limits of Concentration

Concentration of light by optical devices is limited by laws of thermodynamics and optics. When
considering a conventional concentrator based on geometric optics, the concentration is limited
by the conservation of étendue [4,8], which is connected to the second law of thermodynamics.
The concentration ratio in terms of photon density per surface area is characterized by [9]:

\[ C \leq \frac{n^2 \sin^2 \theta_2}{\sin^2 \theta_1} \]  
(1.1)

with \( \theta_1 \) the maximum incident external angle, \( \theta_2 \) the final exit angle and \( n \) the index of refrac-
tion of the concentrator. This means when concentrating diffuse light \( (\theta_1 = 90^\circ) \) the maximum
concentration ratio is \( n^2 \) which is about 2 for most materials. For smaller angles however, the
concentration can be quite effective. When considering direct sunlight in this case, the maxi-
mum concentration ratio is determined by the viewing angle of the sun. This kind of tracking
concentrator can reach a very high concentration factor [4] for direct sunlight, but it requires
active tracking of the sun. For diffuse light on the other hand, the performance is poor.
With luminescent concentrators the situation is different. The incoming light is absorbed and
the absorbed light is Stokes-shifted and re-emitted at a lower energy. The process occurring via
the fluorescent molecule is [9]:

\[ \text{photon}(E_1) \leftrightarrow \text{photon}(E_2) + \text{heat} \]

with \( E_1 \) and \( E_2 \) the photon energies of the absorbed and the emitted photon respectively and
with \( E_1 > E_2 \). This means that the radiance at one energy is increased by converting part of the
incoming photon’s energy to heat. The absorption of the light is not dependent on the incident
angle; the system can operate under all angles. This system does not rely on geometrical optics
and is therefore not limited by equation (1.1). It has been shown that for such a system the
concentration factor in terms of photon density is determined by [2,8]:

\[ C \leq n^2 \frac{E_2^3}{E_1^2} \exp \left( \frac{\Delta E}{kT} \right) \]  
(1.2)

with \( E_1 \) the energy of the absorbed light, \( E_2 \) the energy of the emitted light, \( \Delta E = E_1 - E_2 \)
is the Stokes shift, \( k \) is the Boltzmann constant and \( T \) is the temperature. This shows that
the concentration factor only depends on the Stokes shift and that concentration occurs at the
sacrifice of energy efficiency. In reality, however, this concentration factor is not reached due
to many loss mechanisms (see figure 1.3, the most important of which is the emission in the
escape cone [8,7]).
1.2.4 Photonic Band Pass Mirrors

The loss of fluorescent light through the escape cone can be prevented by covering the top of the LSC with a wavelength selective mirror. This mirror should be transparent in the wavelengths for which the dye is absorbing and reflecting for the wavelengths at which the dye emits so that it will let the sunlight in at the relevant wavelengths and keeps the light emitted by the luminescent material inside the waveguide for all angles. An example of absorption and emission spectra is given in figure 1.4(a). In this figure the filter’s transmission and reflection spectra are squares, which is the ideal situation. Ideally this mirror would have a sharp cut-off edge at the shorter end of the emission spectrum of the luminescent material and be nearly 100% reflective for light of shorter wavelengths coming from all directions [4].

One way to make such mirrors is to use a cholesteric liquid crystal (CLC). In figure 1.4(b) the properties of CLCs are illustrated. As can be seen in the picture, the reflection band of CLCs shifts to shorter wavelengths for light coming in under an angle $\theta$. This will affect the performance of the LSC if the absorption and emission spectrum are close together, like in figure 1.4(a). This is the case because the light emitted by the luminescent particles has a random orientation and will therefore be incident on the CLC under all possible angles and also the sunlight comes in under all angles when the light is diffuse. Because of this, it might happen that under certain angles the CLC blocks incoming solar light that is in the absorption spectrum of the luminescent material and for the same reason it might transmit light from the emission spectrum, thus reducing the efficiency of the system [10]. Another problem when the emission and absorption spectra are overlapping is reabsorption. This means that an emitted photon can be reabsorbed. This reduces the collection probability because the photon can be re-emitted in the escape cone or it can be absorbed by the luminescent particle and converted to heat. To prevent this from happening it is desirable to have a luminescent material with absorption and emission spectra that are further apart, as indicated in figure 1.5. Apart from this the bandwidth of the CLC’s reflection band is important to make sure that light from the emission spectrum will not be transmitted at high angles. Thus a CLC with a broad reflection band is required [8].

---

1 For more on CLCs, see section 1.3
Figure 1.5: Possible emission and absorption spectra of a luminescent material. On the left the emission and absorption spectra overlap. This is undesirable because reabsorption might occur. On the right the absorption and emission spectrum are separated, the desirable situation.

1.2.5 Phosphors

Currently research is being done on phosphors as the luminescent material in the LSC. Ideally this phosphor has a broad absorption spectrum in the visible region and the emission should be a narrow peak at a longer wavelength. The broad absorption spectrum in the visible region is to catch as much sunlight as possible. The emission should be a narrow peak to make sure the cholesteric mirror will be able to reflect the emitted wavelengths at all angles, because as written in section 1.2.4 the reflection band of the CLC will shift for light incoming under an angle. When the emission spectrum is too broad this shift will cause some part of the emission spectrum to be outside the reflection band of the CLC, thus reducing the efficiency of the system. Also, as was indicated in section 1.2.4 because of the shifting of the reflection band, the emission and the absorption spectrum should be well separated to prevent light in the absorption region to be reflected by the CLC.

Another concern for the phosphors is the quantum efficiency (QE). This is the ratio between the number of photons incident on the phosphor and the number of emitted photons. It is of course desirable to have a quantum efficiency that is as high as possible. Phosphors with these properties are currently under development and a phosphor with a QE of at least 99% has already been made and measured.

1.3 Cholesteric Liquid Crystals

1.3.1 Liquid Crystals

The liquid crystal is a state of matter that is intermediate between a crystalline solid and an amorphous liquid; it can be seen as a liquid with an ordered arrangement of molecules. Liquid crystals are formed under certain conditions in organic substances that contain highly anisotropic molecules (rodlike or disklike molecules). The ordering of these anisotropic molecules causes an anisotropy in mechanical, electric, magnetic and optical properties. The states of liquid crystals can be divided into three phases: the smectic phase, the nematic phase and the cholesteric phase. When we consider rodlike molecules the phases can be depicted as in figure 1.6. The smectic phase has a one dimensional translational order and an orientational order. In the nematic phase the only order that exists is that the molecular axes of the molecules are aligned: an orientational order. In the cholesteric phase the molecules are aligned in a nematic
Figure 1.6: Liquid crystal phases [12][11].
way, but it is composed of chiral molecules, meaning that the structure has a twist about a helical axis as shown in the picture. This twist can be right-handed or left-handed. The handedness of the structure is dependent on the chirality of the molecules [11].

1.3.2 Dielectric Constants and Refractive Indices

The molecules we are considering have a rodlike shape, like a cigar. When we look at the dielectric constant in each direction when these molecules are ordered we find that it is different for the material in the direction along the preferred alignment axis ($\epsilon_{||}$) (see figure 1.6 for the axis) with respect to perpendicular to the preferred axis ($\epsilon_{\perp}$). The difference between these values is important for the properties of the material as it influences the ordering of the molecules [11]. The dielectric anisotropy is defined as:

$$\Delta \epsilon = \epsilon_{||} - \epsilon_{\perp}$$

For optical frequencies, $\epsilon_i = \epsilon_0 n_i^2$, with $i$ one of the directions along or perpendicular to the orientational axis. It can thus be written that:

$$\epsilon_{||} = \epsilon_0 n_e^2, \quad \epsilon_{\perp} = \epsilon_0 n_o^2$$

When treated properly a liquid crystal can be obtained with its molecules aligned, all pointing in the same direction. This will cause the slab of material to have a uniform refractive index along the orientation axis of the molecules ($n_e$) and a uniform refractive index perpendicular to the orientation axis ($n_o$). The birefringence of the material is then defined as:

$$\Delta n = n_e - n_o$$

The sign and the value of $\Delta n$ are important factors determining the material properties [11].

1.3.3 Chirality

Chiral objects are objects which cannot be transformed into their mirror image by rotations or translations. Thus, a handedness can be defined for chiral objects. For example, a screw is called right-handed if its windings are clockwise along the screw axis. Otherwise it is called left-handed. The word chirality is derived from the Greek word $\chi\epsilon\iota\rho$, which means hand, because, obviously a hand is also a chiral object. Preference of one-handedness appears everywhere in nature and no less in chemistry and physics [12].

The cholesteric phase appears in organic compounds which consist of elongated chiral molecules. Typical examples of these compounds are derivatives of cholesterol. Because these chiral nematic liquid crystals were first discovered, this type of compounds are generally called cholesteric liquid crystals, even though the name chiral nematic is more correct. On a local scale, a cholesteric material is similar to nematic material. The difference is that the direction $n$ of the preferable orientation of the molecules varies periodically in space, as indicated in figure 1.6(c) [12].

CLCs are often used for optical filtering of circularly polarized light. An example of this is the use in liquid-crystal displays. If the spatial periodicity (helical pitch (p)) is of the same order of magnitude as the wavelength of visible light, the crystals reflect circularly polarized light of the opposite[2] handedness as compared the cholesteric helix and in a wavelength band that depends

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[2]Literature is contradictory about this, because while [13] [14] [12] indicate that CLC layers reflect light of same handedness, in [15] [11] it is stated that CLCs reflect light of opposite handedness. Obviously this is a matter of definition, as there is no disagreement on the experimental results. In this report I will follow the second definition (opposite handedness reflects).

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on the pitch of the helix according to $\lambda = \tilde{n} p$ with $\lambda$ the center wavelength of the reflection band, $\tilde{n} = (n_o + n_e)/2$ and $p$ the pitch. A single pitch cholesteric crystal reflects light with wavelengths between $\lambda_1 = n_o p$ and $\lambda_2 = n_e p$. Within this reflection band left-circularly polarized light is reflected by a right-handed helix, while right-circularly polarized light is transmitted. Outside the reflection band all polarization states are transmitted. By using a gradient pitch it is possible to increase the width of the reflection band. The presence of a range of pitches causes reflection of a range of wavelengths as is illustrated in figure 1.7. In this case the reflection band will be located between $\lambda_1 = n_o p_1$ and $\lambda_2 = n_e p_2$, where $p_1$ is the smallest pitch and $p_2$ is the largest pitch [13]. In general, when $\lambda$ and $p$ are comparable, selective reflection occurs due to Bragg diffraction at a wavelength $\lambda_B$:

$$m\lambda_B = pn \cos \phi$$

With $m$ the diffraction order, $\phi$ the angle of incident light and $n$ the refractive index of the medium. The maximum of the selective reflection at normal incidence occurs at the wavelength $\lambda_B = pn$. The spectral width of the reflection band is $\Delta\lambda = p\Delta n$ with $\Delta n = n_e - n_o$ [12]. For a gradient pitch, the spectral width of the reflection band then is $\Delta\lambda = p_1 n_e - p_2 n_o$.

**Total reflection with a single CLC** It has been described both theoretically [16] and experimentally [17,18] that for a certain combination of angular range and wavelength region a CLC will reflect all the incoming light, independent of the polarization. This effect is possibly caused by the refractive indices $n_e$ and $n_o$ under an angle. When looking at normal incidence $n_e$ and $n_o$ rotate about the axis and so they change direction, but they do not change in amplitude. When looking under an angle, however, the projection of $n_e$ and $n_o$ on the direction of propagation of the light varies in amplitude over the distance traveled in the material, as well as direction. This shifts the reflection band and influences the total reflection.

### 1.3.4 CLC polymers

To make a polymer film with a stable liquid crystal order, photopolymerization of LC monomers can be used. Thin films are formed in the low molar mass state, which is easy to process. Then UV light is used to freeze the LC order, causing network formation and polymerization. The properties of the material can be adjusted by changing the chemical structure of the monomer, blending or by controlling the polymerization temperature. Furthermore, a gradient pitch can be
Figure 1.8: Transmission of circularly polarized light of a monomer blend before and after UV polymerization in the presence of a UV gradient [14].

made by using a UV absorbing dye.

The substances used are:

1. A chiral diacrylate
2. A nematic monoacrylate
3. A photo-initiator
4. A dye which absorbs in the same region as the photo-initiator.

In order to get a gradient pitch, photo-induced diffusion is applied during photopolymerization of the chiral-nematic monomer blend. This will broaden the reflection band of the single pitch material from 40nm to a bandwidth that can be as broad as the whole visible spectrum, depending on the conditions, as shown in figure 1.8.

The diffusion is caused by a UV-intensity gradient over the film thickness and a difference in reactivity between the helix-winding chiral monomer and the helix-unwinding nematic monomer. The UV-intensity gradient can be established with the dye which absorbs in the same region as the photoinitiator. This will cause polymerization at the lamp side of the film to go faster than at the other side. This causes substance 1 to be depleted here faster than substance 2, resulting in a concentration gradient that causes diffusion of the unreacted monomer. The top of the film therefore has more pitch-tightening chiral material while the bottom has more helix-unwinding nematic material. Thus the gradient is formed [14].

**Right- and left handed material**  As is explained previously, right handed material only reflects light of left handed circular polarization. Unpolarized light can be considered as 50% right handed circularly polarized light and 50% left handed circularly polarized light. Thus, to get a total reflection of all the light, a left handed material needs to be combined with a right handed material. This way, the left handed layer reflects all the right handed light and the right handed layer reflects all the left handed light.
In nature right handed materials are more abundant, while left handed materials are more rare. The materials commonly used in liquid crystal displays are right handed. This is why we had an abundance of right handed material on our hands, but no comparable left handed material. Finally we managed to get the left handed material used in [14]. This material has different properties than our right handed material and therefore it needs other conditions to get the same reflection band.

Half lambda Another method to get total reflection of the incoming light is to use a half lambda plate sandwiched between two righthanded CLCs (although left handed materials are suitable for this use as well, it is more convenient to use right handed material because of availability). A half lambda plate is a retarder which swaps the circular polarization direction of the light. When illuminating this configuration with unpolarized light, half the light will be reflected by the first layer. The leftover light is left-handed circularly polarized and cannot be reflected by the right-handed layer. The half lambda reverts the polarization direction. Thereafter, the remaining light is again right-handed polarized and it can be reflected by the second layer.

1.4 Internship

In this report I will present the results of my internship in Philips Research in the ‘Photonic Devices and Materials’ group. During this internship I took part in a project that aims to design a LSC with a cost-efficiency ratio that is suitable for commercialization. The people involved in the project and their roles are:

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1.4.1 Problem Definition

To design a LSC a few tasks need to be fulfilled. The different topics to be addressed are:

- Making the luminescent solar concentrator
- Applying of the luminescent material by coating
- Making the cholesteric liquid crystal

Each of these tasks have their own problems to overcome and they are interdependent, meaning that for example the CLC needs to be adapted to the luminescent material in the LSC. This interdependency is managed through weekly group meetings in which all the group members, who have been working on their specific subject present their results and decisions are taken.
about how to go on. The topic I am working on in this internship is the design of the CLC filter, specifically the theoretical side. The design of a CLC filter poses a number of problems. The practical problems comprise the finding of suitable materials and to prepare the CLC’s. The theoretical problems are to optimize the pitch gradient, thickness and configuration of the layers taking into account that the reflection band shifts when the light comes in under an angle. To optimize these variables for maximum efficiency of the LSC a simulation model needs to be developed. This model then needs to be tested to agree with and used in conjunction with experimental results to optimize efficiency and adapt the CLC to the luminescent material.

1.4.2 Assignment

Thus my assignment is to develop a computer program that calculates characteristics of any configuration of cholesteric layers as a function of wavelength and angle of incidence of the light, to verify that calculations match (optical) experiments and to use this program to do calculations for predicting the characteristics of the CLC and to optimize the CLC for using it on the LSC.

1.5 CLC Theory

As described in section 1.3.2, the cholesteric material is built up from cigar shaped molecules which have two refractive indices, \( n_e \) and \( n_o \), with \( n_e \) the refractive index for light traveling along the orientation axis of the molecules and \( n_o \) for light traveling perpendicular to the orientation axis. The chirality of the material causes the orientation axis to rotate in a helical fashion. The problem is then to find the reflection and transmission characteristics of this layer. An appropriate and flexible way to do these calculations is the 4x4-Matrix Formulation that Berreman proposed in 1971 [19, 20]. In this method, the material properties are approximated by subdividing into a large number of homogenous slabs. Each sublayer is represented by a 4 x 4 matrix and the characteristic matrix of the whole system is the product of the 4 x 4 matrices of all slabs. The boundary conditions at the entrance and at the exit of the medium, together with the characteristic matrix, yield four equations which must be solved in order to get the reflection and transmission coefficients. It is complicated to do this in general, but in some special cases the amount of algebraic manipulations can be reduced significantly. In [20] the characteristic matrices of some special cases are derived. Amongst these special cases is the case where the optic axis is parallel to the plane of stratification (section 3.A of [20]), which is the case for our CLCs. For this case the reflection coefficients are given. The method to acquire these coefficients is used in the program (see section 2.2.3).
Chapter 2

Program

2.1 Introduction

2.1.1 History

In this section I will give a description of the computer program I modified and worked with to model the CLC. At Philips people have been working on a program that simulates transmission and reflection of a CLC layer. The program has originally been written in 1994 and was intended to be used for the design of liquid crystal displays. In these displays CLC layers are used as color filters and it was therefore useful to have a program characterizing the layers in terms of intensity and Stokes parameters\(^1\) of the transmission as well as the reflection. The program has been changed and adapted by different people over the years, resulting in the program I got at the beginning of my internship.

2.1.2 Fortran

The program was written in Fortran 77 and this was, and still is in some areas, the most used programming language at the time of the first version. Apart from that Fortran is also a fast language, best suited for numerical simulations. Over the years, new versions of Fortran have come out, all of which are backwards compatible. By using the GCC compiler I was thus able to use Fortran 90 features to adapt the older program to the current needs.

2.1.3 Common Blocks

A common block is a list of variables and arrays stored in one location which can be accessed by more than one subroutine. The usage of a common block to store variables is generally speaking less desirable than using the argument list mechanism to pass information from one subroutine to another, which makes subroutines modular and it makes it easier to understand the structure of the program. However, when writing a program whose subroutines share a large amount of variables and arrays it is more practical to use the common block. For this program the common block method had been used, save for one subroutine. In my modifications I changed some subroutines (see section 2.4.2) to use the argument list mechanism to be able to do the required

\(^1\)A short introduction into Stokes parameters can be found in [21].
calculations. This, in turn, makes the program structure more clear and it makes it easier for someone else to adapt the program to other needs in the future.

2.1.4 Modifications

Modifications to the program were necessary because the original program calculates for only a single CLC layer. In this project, however, we want to stack multiple layers on top of each other. To do this experimentally tends to take some time, so it is useful to be able to do calculations first to predict the result beforehand so as not to waste time and materials. Moreover, this program is a valuable tool in general and might be used in other projects.

To begin with I started using the program that was supplied in the first place to get familiar with it. A small modification was necessary to allow the program to calculate angle and wavelength dependent results. To plot these results I used Matlab. The next step was to expand the program to calculate for two stacked layers. This allowed me to understand the program structure better which in turn enabled me to modify the program to calculate for a variable number of layers. This new program has been fitted with an explanatory readme and new comments and has been put back into the Philips database.

2.2 Single layer

Calculations are done by using two programs. The original programs have the names ‘gradpitch’ and ‘stokes’. The gradpitch program gets all the input from a single input file and calculates the resultant Jones matrices of the CLC material. This data is then used in the 'stokes' program to calculate the Stokes parameters for a specific polarization of the incoming light.

2.2.1 Principle

The principle of the program is to estimate the optical behavior of the cholesteric material by subdividing it into thin sublayers. These sublayers each have specific and constant properties that reflect the helical structure of the material. This means that each slab of material has the same refractive indices \( n_e \) and \( n_o \), but the slabs have a different orientation. By constantly rotating the slabs the helical nature of the material is simulated. For each slab the transfer matrix is then calculated following the method described in [20]. The matrices are multiplied with each other and with that of an optional birefringent compensator and dichroic polarizer. Subsequently, the propagator matrix is used, together with the angle of incidence to calculate the amplitude of the reflected and the transmitted wave using a method described in [20]. The result is an extended Jones matrix for the reflection and for the transmission. This is done for different wavelengths of incoming light and for different incident angles.

The output file of this program is then used in the stokes program to calculate the Mueller matrices from the Jones matrices via a standard procedure. These Mueller matrices are then applied to the Stokes vector of the incoming light to get the Stokes parameters for each wavelength and incident angle.

---

2 A short introduction into Jones calculus can be found in [21] and a more comprehensive description can be found in [22].

3 A short introduction into Mueller calculus can be found in [21].
2.2.2 Structure

In figure 2.1 the structure of the 'gradpitch' program can be seen.

**getio** The getio subroutine reads the input from the specified input file and stores the values in the common blocks. It then prints the characteristic values of the layer that is to be calculated in the output file. Both input and output file are undefined, meaning that there is no file opened to read or write, but instead the input file and the output file need to be specified when executing the program from the command line. This can be done by running "refpol <inputfile >outputfile". If no output file is specified, the output is printed to the screen.

**init** In this subroutine the values of some variables are defined.

**slice** This subroutine calculates the director profile for a cholesteric film. Input of the programme is the estimated increment of the azimuth angle between each subsequent sublayer, called 'phistp'. Another input is 'twistt', which is the angle (in degrees) between the directors at the two surfaces (modulo 180 degrees). This phistp angle must be such that twistt/phistp and 180/phistp are (nearly) integer values. After the subroutine has been run phistp contains the exact increment value, taking into account the maximum number of sublayers, the cumulative twist over the cell thickness and the boundary condition that azimuth values are to be repeated in subsequent pitches.

**fillrf** This subroutine fills the arrays refthk and refphi with the thicknesses and the azimuth angles of the sublayers according to the results of slice.

**initwl and PTscan** These subroutines are in a loop which runs separately for each wavelength. The initwl subroutine calculates the refractive indices of the material at the appropriate wavelength. The PTscan subroutine then uses this information to calculate the reflection and transmission Jones matrices for each incident angle. The PTscan subroutine uses the Berreman method [19] and the Wöhler simplifications [20] to arrive at the Jones Matrices. A schematic representation of the PTscan subroutine is given in figure 2.2.

2.2.3 PTscan

The subroutine PTscan is where the actual calculations take place. To arrive at these results PTscan calls a number of other subroutines. In figure 2.2 the structure of PTscan is detailed. All the subroutines in PTscan are in loop to calculate for all incident angles. This means that all the subroutines are called once for every angle. As the PTscan itself is in a wavelength dependent loop, the properties of the material are calculated for all incident angles and wavelengths.
first subroutine to be called is Pmatrix. In Pmatrix the transfer matrix of the material is calculated. Next this matrix is inverted in mkPinv (which is needed for the calculations in the next subroutine) and the amplitudes of the stokes vector are calculated in RTampl. Finally the data is written to the output file in wrampl.

**Pmatrix** The Pmatrix subroutine first calls the choles subroutine. The choles subroutine is used to calculate the transfer matrix of the cholesteric layer. To do this, it treats the CLC as a stack of birefringent materials.

The choles subroutine uses the idmat subroutine to set the (undefined at that time) transfer matrix at unity. It then executes the CayP90 subroutine in a loop to calculate the transfer matrix. The loop runs through all the thin sublayers. The calculation in CayP90 is done with using the Cayley-Hamilton theorem as described in [20]. The expressions in section 3A of this article are used as these expressions hold for birefringent layers with the optic axis in the plane of the foil, which is the case in our layers. It then uses newPmx to multiply the result for each sublayer with the result of the previous sublayer, resulting in the transfer matrix for the whole layer at the end of the loop.

Next the Pmatrix subroutine calls the caydic and cayuni subroutines. These subroutines calculate the propagator matrix for a dichroic polarizer and a birefringent compensator. In these subroutines the expressions for the transfer-matrices in [20] (section 3A) and [23] have been used. Pmatrix then uses the newPmx subroutine to multiply the previously acquired matrices to get the transfer matrix of the whole system.

**mkPinv** PTscan then calls mkPinv to invert the transfer matrix in order for it to be used in the next subroutine, RTampl.
This subroutine evaluates the amplitudes of the reflected and the transmitted waves from the (sinus of) the angle of incidence and the inverse of the propagator matrix. Formulas have been copied from [20].

In this subsection the amplitudes of the stokes parameters for the reflected and transmitted wave are written to the output file.

The gradpitch program has now calculated the (extended) Jones matrices for each incident angle and each wavelength.

### 2.2.4 Stokes

Jones calculus is well suited for polarized light, but it cannot describe unpolarized light or partially polarized light. For the calculations, however, we do need unpolarized light. Mueller calculus is the outcome for this, as it is able to work with light of any polarization. The stokes program converts the Jones matrices to Mueller matrices. The polarization of the incoming light is defined beforehand by the user by specifying a Stokes vector. This Stokes vector is then multiplied with the Mueller matrix. The outcome is a Stokes vector for each wavelength and incident angle for the reflected or the transmitted light (dependent on the setting in the program), which has information about the intensity and the polarization of the light.

### 2.3 Double layer Stokes

The first attempt to use the program to calculate for two non-similar layers stacked on top of each other was to use the ‘gradpitch’ program twice: once for the first layer and once for the second layer. The ‘stokes’ program then has to be modified to read the Jones matrices of the two layers and calculate the resultant Jones matrix of the two layers together, taking into account multiple reflections between the layers. In figure 2.3 a schematic depiction of two CLC layers and the multiple reflections that take place between the two layers is given. It can be seen from this figure that when all the transmissions are added up we get:

\[
T_{total} = \sum_{n=0}^{n} (\bar{R}_1 R_2)^n T_1
\]

\[= T_2 (1 - \bar{R}_1 R_2)^{-1} T_1 \]  

This has also been shown in [24]. The only problem now is to find the expressions for the Jones matrices \(\bar{R}_1\) which is the reflection from the underside of the top layer. According to [25] it should be necessary to recalculate the Jones matrix if the light reverses its direction of propagation, but if the optical device is reciprocal it is not needed. In that case the matrix changes according to the expression [25]:

\[
\begin{pmatrix}
m_1 & m_4 \\
m_3 & m_2
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
m_1 & -m_3 \\
-m_4 & m_2
\end{pmatrix}
\]

The stokes program has been modified to calculate the transmission with equation (2.2) and using equation (2.3) for \(\bar{R}_1\). The results of this program, however, did not match expectations as transmissions were higher than 100% for some combinations of angle and wavelength. As far as we can see, the optical elements are reciprocal. The cause of this failure could possibly be
Figure 2.3: When two layers of CLC material are stacked, multiple reflections take place between the two layers. In this figure the transmission and reflection coefficients of some multiple reflections are given.
that the limited precision of calculation causes blowing up of some division in the program. In the end I did not manage to fix this problem so I tried another method which is described in the next section.

2.4 Two and variable number of layers

The next idea to calculate the characteristics of two stacked CLC layers was to make the modification in the gradpitch program. The reason why I didn’t try this before is that it takes more time to use this method to modify the program than to use the method of the previous section.

In the Pmatrix subroutine, the propagator matrix of the CLC layer is calculated by multiplying the individual propagation matrices of all sub-slices which are in turn multiplied with the propagator matrix of the dichroic polarizer and that of the birefringent compensator. After this, the program continues with these matrices and calculates the final Jones matrices, taking into account all the multiple reflection effects through application of the formulas in [20]. The modification I made is to calculate this propagation matrix for the first and for the second layer and multiply them with each other and then with the propagation matrix of the dichroic polarizer and the birefringent compensator. Then the program continues in the normal way, only with a different matrix. The results will then be for two stacked layers and the Stokes program can calculate the Stokes parameters. Later this idea was expanded to calculate for a variable number of stacked layers.

2.4.1 Method Double layer

To make the program suitable for two layers I duplicated all the layer-characteristic variables in the common block for the second layer. This means there is a set of variables that describes the properties of the first layer and another set for the second layer. The variables are shared across all subroutines through the common block. The problem here is that the subroutines used (except fillrf) are not functional (meaning that it doesn’t use the argument list mechanism to pass information from one subroutine to another). Because of this, the subroutines always use the same variables and to call them twice for different variables they have to be duplicated and modified.

getio The getio subroutine has been modified to read the variables for the second layer as well. It reads the data from the input file, just as before, and it writes the values to variables in the common block.

fillrf The fillrf subroutine was already functional. Because of this the only modification required was to call the subroutine twice and let it read from and write to different variables (for the two layers).

slice The slice subroutine is not functional. Because of this it was necessary to duplicate the subroutine and modify the duplicate to read and write from and to the variables of the second layer.

initwl The initwl subroutine was modified to calculate the refractive indices separately for both layers.
The PTscan subroutine itself is unmodified, because the only thing that is dependent on the two layers in this subroutine is buried in the Pmatrix subroutine. This is where the propagation matrices are calculated. The Pmatrix subroutine calls the choles subroutine in which the propagator matrix for a layer is calculated. The choles subroutine is not functional and therefore I duplicated it and modified it to calculate the propagator matrix for the second layer. These matrices are multiplied in the Pmatrix subroutine and the rest of the program runs as before.

2.4.2 Method variable number of layers

For a variable number of layers it is no longer possible to duplicate subroutines for each layer. Because of this it was necessary to make some subroutines functional. Another problem are the variables. In the previous modification I added separate variables for the second layer, but if the number of layers is variable, this is not possible anymore. To solve this problem, each variable was given an extra index, indicating for which layer the data was. This means that scalars become vectors, vectors become matrices and so on. For the structure of the program, please look at figures 2.1 and 2.2 again.

getio For this program the getio subroutine has been redesigned. The old getio read data from the standard input (the input file can be defined when executing the program in the command line). While it is possible to keep on adding data for each extra layer to the same input file, it is more clear to keep the settings in separate files. It is for this reason that I chose to redesign the getio subroutine to read from multiple files. The first file that is read by the subroutine is the "general.in" file. In this file general settings like the number of stacked layers, the wavelength and incident angle range and step and the Stokes vector of the incident light. The program then knows how many layers there are and so it reads the data of each layer from the files "layer1.in", "layer2.in" and so forth till the total number of layers is reached. The data is stored in the variables with an extra index for the layer number. The getio subroutine writes the properties of each layer to the output file.

slice To calculate the director profile for the multiple stacked layers I modified the slice subroutine by making it functional. This means that variables are fed into and given back by the subroutine by the argument list mechanism. This, in turn, makes it possible to incorporate the slice subroutine in a loop which runs for all the sublayers. For each sublayer the variable with the corresponding extra index for the layer number is supplied to the subroutine.

fillrf The fillrf subroutine was already functional. Because of this, the only modification necessary was to incorporate it into the same loop as the slice subroutine and to change the variables to indicate the layer number in the extra index.

initwl As previously mentioned initwl and PTscan are in a loop which covers the wavelengths. The initwl subroutine calculates the refractive index for each wavelength. To do this for all layers, an extra loop was incorporated in the initwl subroutine. This loop calculates the refractive indices separately for each layer and puts them back in the common block.

PTscan Once again the PTscan subroutine itself is unaltered, but the Pmatrix subroutine that is called by PTscan is modified. As was described in section 2.2.3 the Pmatrix subroutine calls the choles subroutine, the caydic subroutine and the cayuni subroutine to calculate the propagator.
matrices for the CLC material, the dichroic polarizer and the birefringent compensator respectively. To do this for a variable number of layers, a loop was used. The loop first calculates the propagator matrices for all CLC, dichroic polarizer and birefringent compensator layers and then multiplies them in the order so that the polarizer and compensator are always on top of the CLC material. For this to work, the choles, the caydïc and the cayuni subroutine have been modified to read the variables of the layers with the extra index, indicating the layer number.

2.4.3 Stokes

The stokes program has been modified to read the output file of the new gradpitch program. The difference with the old program is that the output now has the properties of all (variable number) of layers in it. The gradpitch output file indicates the total number of layers. This number is used by the stokes program to determine the line of the output file where it is supposed to begin reading the Jones matrices. For the rest, the stokes program is unchanged.

2.5 Matching the simulation to the experiment

To match the simulations to the experiments, a few data are needed. First of all, the \( n_e \) and \( n_o \) of the CLC material need to be known. Secondly, a spectrometer measurement of the CLC material at normal incidence is used to determine the position and width of the reflection band. As can be seen from section 1.3.3 it is possible to determine the pitch gradient from these data, assuming a linearly varying pitch. From this, wavelength and angle dependent results can be calculated, predicting the behavior of the samples under different circumstances.
Chapter 3

Results and discussion

3.1 Set-up

Measurements on the CLC samples were done with a Perkin-Elmer Lambda 800 UV-VIS Spectrophotometer. This device has a sampleholder that is rotatable, which enables us to do angle dependent transmission measurements. To eliminate refraction of the light under angles, the sample was sandwiched between two half-cylinders and index-matching oil was applied. In figure 3.1 the experimental set-up is shown. The second lightbeam going into the detector is the reference lightbeam.

3.2 Single CLC

3.2.1 Checking measurements

Results  The first and most simple measurements are on a gradient pitch single CLC layer at different angles. The refractive indices of the material are $n_e = 1.68$ and $n_o = 1.54$. The results of the measurements are shown in figure 3.2 together with the calculations for the respective configurations (for settings of the program see page 41). To fit the calculations to the measurements, the pitch of the material in the calculation is adapted so that the left and the right side of the reflection band match in calculation and experiment at normal incidence (0 degrees). For the pitch gradient we find $p_1 = 447$nm and $p_2 = 536$nm. From this, the other cases are calculated.

Figure 3.1: Experimental set-up for measuring transmission spectra of CLC layers. The pink lines indicate lightbeams.
Figure 3.2: Transmission spectra of a right handed CLC at various angles. Red lines indicate the experiment, blue lines indicate calculations.

Discussion  As can be seen, the curves of the calculation are quite accurate when comparing them to the actual measurement. The measurements show a lower transmission in general. This can be explained by scattering of the sample, which is not taken into account in the calculations. Furthermore it can be seen that the calculations have more oscillations than the experiment. It can be seen from calculations that the frequency of the oscillations is dependent on the thickness of the sample and that the location of the oscillations is dependent on the incident angle of the light (section 3.2.2). The difference between calculation and experiment can thus be explained by the variation in thickness of the sample and the angular divergence and size of the spot of the light. This is because in the calculation the sample has a constant thickness everywhere, while the experimental reality is that the thickness of the sample varies from spot to spot. In the experiment the illumination spot on the sample is a few mm wide, which allows for thickness variation. Furthermore, as we will see in section 3.2.2 the oscillations are angle dependent. The angular divergence of the light in the spectrometer has an uncertainty of ±2 degrees, which also contributes to the suppression of the oscillations.

Physical explanation  As noted in section 1.3.3 when the light is incident on the material at an angle, the refractive indices perceived by the lightbeam are changed. Instead of the refractive indices at normal incidence, the projection of the refractive indices at the angle is perceived. Therefore the reflection band, which is between $\lambda_1 = n_o p_1$ and $\lambda_2 = n_e p_2$ as mentioned in
section 1.3.3, is shifted to shorter wavelengths. This is because the projections of $n_e$ and $n_o$ are smaller than $n_e$ and $n_o$ at normal incidence. This explains the shift to shorter wavelengths of the reflection band in the measurements under angles. The oscillations that are apparent in the calculations can be attributed to interference. These are not visible in the experiment due to reasons discussed in the Discussion paragraph of this section.

**Total reflection of a single CLC layer at an angle** As has been described in [18, 17, 16] and section 1.3.3 a single CLC can reflect all incoming light in a wavelength region at a certain angular range. We found this both experimentally and by calculation, as can be seen in figure 3.2 at 60 degrees.

### 3.2.2 Angle dependent calculations

**Results** Now that it has been established that the calculations are quite accurate when comparing to the experiments, it is possible to use the simulations to predict the behavior of the CLC layer under different circumstances. In figure 3.3 a calculation of the reflection of a right handed material in air is shown. The settings used for this simulation can be found in the appendix on page 41. In this calculation the incident light is left handed circularly polarized and should thus be totally reflected in the reflection band.

**Discussion** In this graph the shift of the reflection band under higher angles is apparent and is as expected. Also, we see oscillations in this graph, just as in the previous results. It is visible that they shift in the same way as the reflection band when changing the angle. At angles near 90 degrees for almost all wavelengths the incoming light is reflected. This is due to total reflection at the interface. A striking feature is the reduction in reflectivity on the right side of the reflection band at incident angles around 60 degrees. In section 3.4.4.1 I will investigate what happens to the handedness of the polarization in this case.
Figure 3.4: Transmission spectra of a right handed CLC stacked on top of a left handed CLC. Red lines indicate the experiment, blue lines indicate calculations.

3.3 Double CLC

3.3.1 Left- and right-handed material

**Results** The next step is to measure the transmission spectra of a configuration of stacked CLCs. In this experiment a right-handed CLC is stacked on top of a left-handed CLC. The samples were made to have identical reflection bands, so they can combine to make a wavelength selective mirror. It is to be expected that in this case, light of all polarizations is reflected in the reflection band. The results are shown in figure 3.4 together with the calculations for the respective situations. For the calculations, separate measurements were done on the individual samples at normal incidence (these results are comparable with the single layer results in section 3.2.1). These measurements were used to characterize the samples and thereafter the program was used to calculate the transmission spectrum of the configuration of the stacked samples. The pitches I found were \( p_1 = 437.01 \text{nm} \) and \( p_2 = 520.24 \text{nm} \) for the right handed material and \( p_1 = 429.22 \text{nm} \) and \( p_2 = 521.43 \text{nm} \) for the left handed material. The \( n_e = 1.68 \) and \( n_o = 1.54 \) were the same as before for both samples. Settings of the program can be found in the appendix on page 41.

**Discussion** As expected, the transmission goes almost to 0 in the reflection band and the experimental results follow the calculations reasonably well. As before, we see more oscillations in the calculations than in the experimental results and this is due to the same reasons as mentioned in section 3.2.1. The reflection band of the sample is slightly more narrow in the experiment than in the calculation. This might be due to the fact that we measured the individual samples (for characterization and determination of parameters for usage in the program) and put the variables for each layer into the program separately. As a result, the final measurements are not on
the exact same spots as the characterizing measurements were done. As can be expected from a sample, the properties vary slightly from spot to spot, which in turn can explain the slightly different reflection band.

**Physical explanation**  
As explained in section 3.2.1, the reflection band of a single CLC shifts under an angle. This holds for both left-handed and right-handed material. The left-handed material reflects right-handed light and the right-handed material reflects left-handed light. The reflected light retains its polarization. This ensures that the light that is reflected by the second layer is not reflected again by the first layer when it travels back. So in the end, all light is reflected in the wavelength region where the reflection bands of the right-handed and the left-handed material overlap.

This description is valid at normal incidence. At angles, however, the situation changes because the light becomes elliptically polarized. In this case it is more difficult to give a physical explanation that satisfies intuition. What will happen is that the reflected light gets elliptically polarized. This means that the light that is reflected by the second layer has to pass through the first layer again, while being elliptically polarized. You might expect this to effect in another reflection in the first layer sending the light back in again, reducing performance of the reflection. Apparently this does not happen and the ellipticity of the light is compatible with the properties of the material at an angle, allow the reflection band to be there, although at a shifted wavelength.

### 3.3.2 Half lambda configuration

**Results**  
The other method of getting total reflection is the usage of a half-lambda wave plate. This plate reverses the polarization direction of light passing through it. This means that left-handed circularly polarized light is turned into right-handed circularly polarized light and vice versa. The configuration used in this experiment is a half-lambda plate sandwiched between two right-handed CLC layers. The results are shown in figure 3.5 and the settings of the program can be found in the appendix on page 43.

**Discussion**  
It can be seen that the experimental results match the calculations quite well. Once again, the oscillations that are in the calculation are not visible in the experimental results, but appear to be averaged, for reasons previously mentioned. In previous measurements the reflection was not a total reflection, as it is in this measurement. A probable explanation for this is that half-lambda waveplates only work optimally for a specific wavelength. With the waveplate we used then, this wavelength was at 550nm. By combining two waveplates, we managed to create a half wave plate with the center wavelength at 825nm, of which the result is shown. It can be seen that this configuration has a good total reflection in the reflection band. The wave plates used are thin foils previously used for LCS’s and they were made in Japan. We used a half wave plate and a quarter wave plate combined.

The matching of the calculation of the experiment was done by measuring the two right-handed materials separately and matching the reflection band of those measurements to the calculation. The program then calculates the transmission for the combination of the two samples. The two reflection bands of the right-handed samples matched quite good, but the position differed a few nanometers. Also, the properties of the sample vary over the sample. These two facts can be an explanation for the slight mismatch between the reflection bands of the calculation and the

---

The half wave plate has description: Zeonor 225nm, the quarter wave plate: NRF-QF-01A
Figure 3.5: Transmission spectra of a configuration where a half-lambda plate is sandwiched between two right-handed CLC layers.

experiment, which is most apparent at low angles.

Furthermore, the transmission is lower overall in the experiment, which is probably due to scattering in the samples, as was noted earlier.

Physical explanation   The first layer (which is right-handed) reflects all left-handed light. The remaining right-handed light is then converted to left-handed light by the half-lambda waveplate. Next, this left-handed light is reflected by the second right-handed layer, resulting in total reflection of light of all polarizations. The light that is reflected by the second right-handed layer (which is left-handed) is converted again by the wave plate, when going back, to right-handed light, which enables it to be transmitted through the first right-handed layer, being successfully reflected. The first layer had already reflected the other half of the incoming light, resulting in a total reflection of light of all polarizations in the reflection band.

3.3.3 Angle dependent calculations for left- and right-handed material

Results   Just as I did before with the single layer, it is now possible to have the program calculate the behavior of the CLC in more detail for all angles and wavelengths. This will give us a good idea if the stacked CLCs are performing as required and make it possible to compare the different configurations with each other. The result for the combination of the right- and left-handed CLCs is shown in figure 3.6 and settings for the program can be found in the appendix on page 42.

Discussion   As the reflection bands of the right- and left-handed CLCs are matched to each other in this calculation, it is to be expected that the reflection band has the same width and
position as was the case for the single layer. Oscillations are visible in this result as well. The layers are perfectly identical in every respect, save for the sign of the chirality. Therefore you would expect the oscillations of both layers to overlap and add up. We see in this result, however, that the oscillations are different and more abundant than in the single layer result. An error in the previous reasoning is that it doesn’t take into account the thickness of the layer. The oscillation frequency increases with thicker layers. This is because the fringes are caused by interference. When traveling through a thicker material, the phase difference that is obtained is bigger. This causes the fringes to be closer together in terms of wavelength. In this case we have two layers added together, which in effect doubles the thickness, explaining the increase in oscillation frequency.

3.3.4 Angle dependent calculations for half lambda configuration

Results The same can be done for the half lambda configuration. Here a half lambda with a center wavelength of 690nm is used. This wavelength is chosen because it effects in the filter being most efficient around the reflection band as will be discussed in section 3.4.2. The results are shown in figure 3.7 and the settings for the program can be found in the appendix on page 44.

Discussion This reflection band is comparable to the previous result with the right- and left-handed materials. One of the differences is the frequency of the oscillations. The oscillations are different in this case because of the thickness of the half wave plate, which is about 200nm in this configuration. The operation of the half wave plate is dependent on the frequency of the light that passes through it. Combined with the two right-handed layers, this causes more oscillations in the calculations. Another difference with the previous section is the lack of the 'weak spot' on the higher wavelength side of the reflection band near 60 degrees. This is probably due to the half wave plate and a possible explanation for this is given in section 3.4.4.
3.3.5 Double layer comparison

Now that we have looked at these two configurations that both have a total reflection band in the wavelength region required by the design of the LSC. To make a choice in the design of the LSC the theoretical results, the experimental results and the feasibility of both options need to be considered.

**Theoretical** To compare the theoretical results we look at figures 3.6 and 3.7. It can be seen in these graphs that both configurations have a reflection band of the same broadness in the same place. A difference between the figures is that the right- and left-handed configuration has a ‘weak spot’ in the 680-780nm region at angles between 50 and 80 degrees. This weak spot reduces performance of the system and is not desirable. The other configuration with the half wave plate does not have the ‘weak spot’.

**Experimental** To compare the experimental results we look at figure 3.4 and 3.5. It can be seen that both configurations have a good reflection band of the same width at about the same location for each incident angle. In both experiments scattering in the sample is apparent at wavelengths outside the reflection band. This is comparable for both cases. At normal incidence the results are in general comparable, but when looking at higher angles, there are differences between the two cases. As can be seen in figure 3.5 the performance of the reflection band decreases for the half wave plate configuration when looking at angles higher than 20 degrees. In the calculation the half wave plate configuration had a better reflection at angles than the left- and right-handed configuration.

The ‘weak spot’ can be seen in the experiments as well and, as expected from the calculations, it is only apparent in the right- and left-handed material. In the graphs of figure 3.4 a weak spot can be seen on the right hand of the reflection band. These angles are different than in the calculation because the calculation was in air and the measurement was done in a cylinder with index matching oil.

Figure 3.7: Reflection spectrum of a configuration where a half-lambda waveplate is sandwiched between two right-handed CLC layers in air as a function of incident angle and wavelength.
Feasibility For the final design of the LSC the feasibility of each option is important. Both have their positive points and their drawbacks.

Half wave While the half wave plate configuration is in theory the best performing, in experiment it performed less than the right- and left-handed configuration. This might be a problem with the half-wave plate and it might be solved by finding a better wave plate or making better samples. The other problem with this configuration is the complexity of the combination of layers. The half wave plate may be made from the same process with the same kind of reactive mesogens, but requires three layers and it may be difficult to avoid scattering at the interfaces. Also see section 3.3

Left- and right-handed The problems with the right- and left-handed configuration are the availability of left-handed material. Although we have some of this material available at the moment it is not a readily available substance and to obtain it in large quantities might pose some problems. The other problem is the complexity of the process needed to match the reflection bands of the right- and left-handed materials. This tuning takes some time and in a production environment it might make things more expensive. Also see section 3.2

3.4 Other Results

3.4.1 Varying thickness

Results At each sublayer in the material light is reflected. The question is how much light is reflected and how thick the materials should be to reflect all the incoming light. From the perspective of economics, it is interesting to be able to minimize the amount of used material. Therefore I did some calculations to determine the reflection of a combination of a right- and a left-handed filter in the wavelength region of 720-740nm (the region we are interested in) as a function of the thickness of the individual layers. The result is shown in figure 3.8. The settings for the program used in this calculation can be found in the appendix on page 44. In this simulation the pitches were set to fit the reflection band at normal incidence to a sample we have. The 1/2 pitch varied from 447nm to 536nm, which means that one micron is about one pitch (a rotation of 360 degrees).

Discussion It can be seen that the reflection increases exponential with thickness of the sample. When each new added sublayer reflects a certain fraction of the incoming light, this behavior is to be expected. A thickness of 15 micron (which is about 15 full rotations) is needed to obtain a reflection of 87%.

3.4.2 Varying half lambda center wavelength

Results By changing the center wavelength (in calculation) of the half wave plate in the configuration where a half wave plate is sandwiched between two right-handed layers, the peak efficiency (reflectance) of the configuration can be determined. The efficiency is dependent on the center wavelength of the wave plate because the half wave plate inverts the polarization direction the best exactly at the point where it is centered. At other points the polarization becomes elliptical after passing through the wave plate, thus reducing the amount of circularly (and thus reflectable by the second layer) polarized light. We have to find an optimum between reflection
in the region 720-740nm (because this is the region where the phosphor emits) and transmission in the region 600-700nm, because this is the longest end of the absorption spectrum of the phosphor. Results of calculations are shown in figure 3.9. Here, the transmission/reflection was calculated for the complete angular and wavelength range and integrated and normalized over the wavelengths (720-740nm and 600-700nm) and the angles (from 0 to 90 degrees). Settings for the program can be found in the appendix on page 45.

Discussion

For this calculation we would expect the optimal center wavelength for reflectance in the region 720-740nm to be near this wavelength. What we observe is an optimum between 640-680nm. This is lower than expected and it is probably due to a change in the properties of half wave plates when illuminated under an angle.

For the transmission in the 600-700nm region, we would expect it to be most efficient when the center wavelength of the wave plate is furthest away from it, because if it is far away, the polarization becomes more elliptical than circular. Consequently the second layer reflects less of the light. This is what we observe.

3.4.3 Quad layer CLC

Results

Another method to get a broadband device is to combine even more layers, but this time with a constant pitch. In this case two sets of right- and left-handed material are stacked so that in total 4 layers are used. The reflection bands of the single pitch materials will be matched so that they combine to form a broad reflection band. A reason to make the reflector in this way is that it is easier to make a constant pitch device than it is to make a CLC with a gradient pitch. Therefore it was considered to use this method for demonstration purposes. To investigate the expected performance of such a configuration, calculations were done. The results are shown in figure 3.10 and the settings for the program can be found in the appendix on page 45.

Discussion

From separate calculations of the right- and left-handed layers for each reflection band, it can be seen that the reflection band is the combination of the two separate reflection bands. The reflection band is still less broad than what can be achieved when using a gradient
Figure 3.9: Transmission in the 720-740nm wavelength region as a function of the half wave plate central wavelength. The sample is a sandwich of a half wave plate with two right-handed CLC layers.

pitch material. Adding two more layers will solve this problem, but might be more difficult in practice.

Another noteworthy feature of this result is that the reflection of this configuration is better than in the gradient pitch configuration and that the cutoff at the reflection band is steeper. These features increase performance, whereas the downside of this configuration is that more material is used and that combining more materials requires a more complicated fabrication process.

3.4.4 S3 polarization single layer

Results The output of the program are the Stokes vectors of the transmission or the reflection for each wavelength and incident angle. The Stokes vectors can tell us more, however, than just the transmission and the reflection intensities. They can help us understand what happens with the polarization of the light in between the layers.

To investigate what happens with the handedness of the circular polarization after passing through a right-handed layer, and what happens if it passes through a half wave plate subsequently, I plotted the S3 component of the Stokes vector for incoming left-handed light. The results are shown in figure 3.11 and figure 3.12 respectively. In these graphs a positive value stands for right-handed polarized light and a negative value stands for left-handed polarized light.

Discussion In figure 3.11 it can be seen that around the weak spot, which was discussed earlier, the direction of the circularly polarized light is reversed. When looking at figure 3.12 it can be seen that the half wave plate annuls this effect for the most part. This enables the half lambda configuration to eliminate the weak spot, while the combination of right- and left-handed material retains the weak spot.

---

A short introduction into Stokes vectors can be found in [21].
Figure 3.10: Transmission in the 720-740nm wavelength region as a function of the half wave-plate central wavelength. The sample is a sandwich of a half wave plate with two right-handed CLC layers.

Figure 3.11: The S3 Stokes parameter for different incident angles and wavelengths of the transmitted light after passing through a right-handed CLC with a pitch gradient (settings for the program can be found in the appendix on page 47).
Figure 3.12: The S3 Stokes parameter for different incident angles and wavelengths of the transmitted light after passing through respectively a right-handed CLC with a pitch gradient and a half wave plate (settings for the program can be found in the appendix on page 47).
Chapter 4

Conclusion

4.1 Agreement program/experiment single layer

As can be seen in section 3.2.1, calculations match the experiment quite well. The shape and the position of the reflection band are accurately predicted. The information used for these predictions is the position and width of the reflection band at normal incidence, together with the $n_e$ and $n_o$ of the material. It can be concluded from this that the method used by the program is a valid method to predict the behavior of the CLCs at an angle.

Another thing to note is that the current sample is scattering, as the transmission is lower than the simulation outside the reflection band. This issue needs to be addressed when designing the LSC.

4.2 Right- and left-handed material

The next test is to see if the calculations of the modified program hold for stacked layers as well. This was done in section 3.3. Again, there is agreement between the calculation and the experiment, although the reflection band is less broad in the experiment for reasons previously mentioned in section 3.3. It can be concluded that the modified program accurately predicts the behavior of two stacked layers for different incident angles and wavelengths of the light.

Also, this configuration has a good total reflection in the reflection band, thus it is suitable for usage in the LSC.

4.3 $\lambda/2$ Configuration

The same holds for the configuration with the half wave plate. Predictions of the program are accurate for measurements at different angles and wavelengths.

The downside to this configuration however, is that reflection decreases at higher angles in the experiment (as opposed to in the calculation). This is an indication that this configuration could be less suitable to use in the LSC than the combination of the left- and right-handed material, which does not have that problem.
4.4 Optimal thickness CLC layer

In the graph of figure 3.8, it can be seen that above a thickness of about 15 micron the reflection does not increase much anymore. Apparently about 15 pitches are necessary to reflect most of the incoming light. On the other hand, it is a matter of cost. When deciding the final thickness of the layer, the costs of the material need to be balanced with the gain in performance due to a higher reflectance as a function of thickness.

4.5 Optimal \(\lambda/2\) center wavelength

The graph in figure 3.9 shows an optimum reflection in 720-740nm when the half lambda is centered around 640-680nm. The transmission in the 600-700nm region is best when a center wavelength of 400nm is chosen. It is, however, more important to have a good reflection in 720-740, because the absorption spectrum extends further than 600nm. For this reason it is most logical to choose a half lambda with a center wavelength around 640nm, approximately 10% lower than the emission wavelength.

4.6 Quad layer configuration

As the calculations in figure 3.10 show, it is possible according to calculations to make a broadband reflector by combining non-broadband reflectors. Although this is not the most efficient method to make a LSC, it might be useful for demonstration purposes.

4.7 Outlook

**Added value**  When I came into this project, work had been done on the phosphors, the applying of the phosphors onto lightguides and some CLC samples had been made. During the course of my internship we advanced on all levels and with the CLC specifically we made big experimental and theoretical steps. The drive has always been to actually make good reflectors with the CLCs. In the process of making the good reflectors, I have contributed by giving predictions with the calculations made by the program. These predictions have been helpful in making decisions for how to make the CLC. On the other hand, the modifications I made to the computer program allow it to calculate the characteristics of any configuration of cholesteric layers. This program can now be used within Philips or TU/e in this project, but it can also benefit other projects in the future.

**Recommended course of action**  At this point in the project we have some good results. We have the choice between two (or maybe more if the quad layer configuration is considered as well) options for the wavelength selective mirror which both have been proven in experiment to work. Then we have a phosphor with a broad absorption spectrum, a narrow emission spectrum and a quantum efficiency higher than 99%. Also the procedure of applying the phosphor onto the lightguide is improving. Plans are there to make a 10x10cm demonstrator soon. This means that most of the crucial ingredients for the LSC are getting along on schedule. The things that need to be done next are making design choices (dimensions, type of solar cell, type of phosphor) and adapting the CLC to that (fitting the reflection band to the emission spectrum of the phosphor). The actual manufacturing of the LSC will not be done by Philips, so a partner company with
expertise in solar cells needs to be found to negotiate a final product release. This is a whole other process in which testing needs to be done once more. In this case durability, reliability and cost of the product will be of central concern.

Acknowledgement

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Bibliography


**Appendix**

**Parameters**

**Single layer CLC - simulations to match experiment**

Program used: Single layer
1 0 0 0 Stokes vector incident light
15d0 10000 thickness maximum number of sublayers
0.44747d0 0.53620d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
300d-3,900d-3,1d-3,1 golflengte: van, naar, stap, aantal substappen
0d0 80d0 20d0 polar angle: start end step
0d0 0d0 5d0 azimuth angle: start end step
0d-3,45d0 thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1. 0d-3 0d-5 Nreal, Nimpar and Nimprp for dichroic polar
1.49d0 1.49d0 refr. index surrounding medium (incident, transmitted)

Single Layer CLC - angle dependent measurements
Program used: Double layer

1 0 0 -1 Stokes vector incident light
15d0 10000 thickness maximum number of sublayers
0.44747d0 0.53620d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
300d-3,900d-3,1d-3,1 golflengte: van, naar, stap, aantal substappen
0d0 89.5d0 .25d0 polar angle: start end step
0d0 0d0 5d0 azimuth angle: start end step
0d-3,45d0 thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1. 0d-3 0d-5 Nreal, Nimpar and Nimprp for dichroic polar
1.d0 1.d0 refr. index surrounding medium (incident, transmitted)
15d0 thickness second layer
0.44747d0 0.53620d0 pitch second layer
1.d0,0d0,0d0,0d0,0d0 rie-coeff second layer
1.d0,0d0,0d0,0d0,0d0 rio-coeff second layer

Right- and left-handed CLC - simulations to match experiments
Program used: Variable number of layers

general.in:
2 number of stacked layers
1 0 0 0 stokesvector incident light
300d-3,900d-3,1d-3,1 golflengte: van, naar, stap, aantal substappen
0d0 60d0 10d0 polar angle: start end step
0d0 0d0 5d0 azimuth angle: start end step
1.49d0 1.49d0 refr. index surrounding medium (incident, transmitted)

layer1.in:
15d0 10000 thickness maximum number of sublayers
0.43701d0 0.52024d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
0d0 3,45d0 thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1d0 0d-3 0d-5 Nreal,Nimpar and Nimprp for dichroic polar

layer2.in:
15d0 10000 thickness maximum number of sublayers
-0.42922d0 -0.52143d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
0d0 3,45d0 thickness and azimuth compensator
1.6d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1d0 0d-3 0d-5 Nreal,Nimpar and Nimprp for dichroic polar

Right- and left-handed CLC - angle dependent calculations
Program used: Double layer
Half lambda configuration - simulations to match experiment
Program used: Variable number of layers

general.in:
2
number of stacked layers
1 0 0
stokesvector incident light
300d-3,900d-3,1d-3,1
golflengte: van, naar, stap, aantal substappen
0d0 70d0 10d0
polar angle: start end step
0d0 0d0 5d0
azimuth angle: start end step
1.49d0 1.49d0
refr. index surrounding medium (incident, transmitted)

layer1.in:
15d0 10000
thickness maximum number of sublayers
0.46364d0 0.52321d0
estimated pitch
1.68d0,0d0,0d0,0d0,0d0
rie-coef
1.54d0,0d0,0d0,0d0,0d0
rie-coefficients
0d-3,45d0
thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0
rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0
rie-coefficients compensator
0d0 0d0
thickness and azimuth for dichroic polarizer
1. 0d-3 0d-5
Nreal,Nimpar and Nimprp for dichroic polar
1.d0 1.d0
refr. index surrounding medium (incident, transmitted)
15d0
thickness second layer
-0.44747d0 -0.53620d0
pitch second layer
1.68d0,0d0,0d0,0d0,0d0
rie-coeff second layer
1.54d0,0d0,0d0,0d0,0d0
rie-coeff second layer

layer2.in:
15d0 10000 thickness maximum number of sublayers
0.46364d0 0.52321d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
4125d-3,45d0 thickness and azimuth compensator
1.6d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1d0 0d-3 0d-5 Nreal,Nimpar and Nimprp for dichroic polar

Half lambda configuration - angle dependent calculations
Program used: Double layer

1 0 0 0 Stokes vector incident light
15d0 10000 thickness maximum number of sublayers
0.44747d0 0.53620d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
300d-3,45d0 thickness and azimuth compensator
0d0 89.5d0 .25d0 polar angle: start end step
0d0 0d0 5d0 azimuth angle: start end step
1976d-3,45d0 thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1. 0d-3 0d-5 Nreal,Nimpar and Nimprp for dichroic polar
1.d0 1.d0 refr. index surrounding medium (incident, transmitted)
15d0 thickness second layer
0.44747d0 0.53620d0 pitch second layer
1.68d0,0d0,0d0,0d0,0d0 rie-coeff second layer
1.54d0,0d0,0d0,0d0,0d0 rio-coeff second layer

Thickness variation
Program used: Double layer
1 0 0 0  Stokes vector incident light
8d0 10000  thickness maximum number of sublayers
0.44747d0 0.53620d0  estimated pitch
0d0 0d0 10d0  phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0  rie-coef
1.54d0,0d0,0d0,0d0,0d0  rio-coefficients
300d-3,900d-3,1d-3,1  golflengte: van, naar, stap, aantal substappen
0d0 89.5d0 .25d0  polar angle: start end step
0d0 0d0 5d0  azimuth angle: start end step
0d-3.45d0  thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0  rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0  rio-coefficients compensator
0d0 0d0  thickness and azimuth for dichroic polarizer
1. 0d-3 0d-5  Nreal,Nimpar and Nimprn for dichroic polar
1.d0 1.d0  refr. index surrounding medium (incident, transmitted)
8d0  thickness second layer
-0.44747d0 -0.53620d0  pitch second layer
1.54d0,0d0,0d0,0d0,0d0  rie-coeff second layer
1.68d0,0d0,0d0,0d0,0d0  rio-coeff second layer

Varying half lambda center wavelength
Program used: Double layer

1 0 0 0  Stokes vector incident light
15d0 10000  thickness maximum number of sublayers
0.44747d0 0.53620d0  estimated pitch
0d0 0d0 10d0  phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0  rie-coef
1.54d0,0d0,0d0,0d0,0d0  rio-coefficients
300d-3,900d-3,1d-3,1  golflengte: van, naar, stap, aantal substappen
0d0 89.5d0 .25d0  polar angle: start end step
0d0 0d0 5d0  azimuth angle: start end step
500d-3,45d0  thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0  rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0  rio-coefficients compensator
0d0 0d0  thickness and azimuth for dichroic polarizer
1. 0d-3 0d-5  Nreal,Nimpar and Nimprn for dichroic polar
1.d0 1.d0  refr. index surrounding medium (incident, transmitted)
15d0  thickness second layer
0.44747d0 0.53620d0  pitch second layer
1.54d0,0d0,0d0,0d0,0d0  rie-coeff second layer
1.68d0,0d0,0d0,0d0,0d0  rio-coeff second layer

Quad layer CLC
Program used: Variable number of layers

general.in:
number of stacked layers
1 0 0 0 stokesvector incident light
300d-3,900d-3,1d-3,1 golflengte: van, naar, stap, aantal substappen
0d0 89.5d0 .25d0 polar angle: start end step
0d0 0d0 5d0 azimuth angle: start end step
1.d0 1.d0 refr. index surrounding medium (incident, transmitted)

layer1.in:
15d0 10000 thickness maximum number of sublayers
0.46039d0 0.46040d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
0d-3,45d0 thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1d0 0d-3 0d-5 Nreal,Nimpar and Nimprp for dichroic polar

layer2.in:
15d0 10000 thickness maximum number of sublayers
-0.46039d0 -0.46040d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
0d-3,45d0 thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1d0 0d-3 0d-5 Nreal,Nimpar and Nimprp for dichroic polar

layer3.in:
15d0 10000 thickness maximum number of sublayers
0.50195d0 0.50196d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
0d-3,45d0 thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1d0 0d-3 0d-5 Nreal,Nimpar and Nimprp for dichroic polar

layer4.in:
15d0 10000     thickness maximum number of sublayers
-0.50195d0 -0.50196d0 estimated pitch
0d0 0d0 10d0     phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
0d-3.45d0 thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1d0 0d-3 0d-5 Nreal,Nimpar and Nimprp for dichroic polar

S3 Stokes parameter Right CLC
Program used: Double layer

1 0 0 -1     Stokes vector incident light
15d0 10000 thickness maximum number of sublayers
0.44747d0 0.53620d0 estimated pitch
0d0 0d0 10d0 phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0 rie-coef
1.54d0,0d0,0d0,0d0,0d0 rio-coefficients
300d-3,900d-3,1d-3,1 golflengte: van, naar, stap, aantal substappen
0d0 89.5d0 .25d0 polar angle: start end step
0d0 0d0 5d0 azimuth angle: start end step
0d-3.45d0 thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0 rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0 rio-coefficients compensator
0d0 0d0 thickness and azimuth for dichroic polarizer
1.d0 1.d0 refr. index surrounding medium (incident, transmitted)
15d0 thickness second layer
0.44747d0 0.53620d0 pitch second layer
1.d0,0d0,0d0,0d0,0d0 rie-coeff second layer
1.d0,0d0,0d0,0d0,0d0 rio-coeff second layer

S3 Stokes parameter Right CLC + half wave plate
Program used: Variable number of layers

general.in:
2 number of stacked layers
1 0 0 -1 stokesvector incident light
300d-3,900d-3,1d-3,1 golflengte: van, naar, stap, aantal substappen
0d0 89.5d0 .25d0 polar angle: start end step
0d0 0d0 5d0 azimuth angle: start end step
1.d0 1.d0 refr. index surrounding medium (incident, transmitted)

layer1.in:

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15d0 10000  thickness maximum number of sublayers
0.44747d0 0.53620d0  estimated pitch
0d0 0d0 10d0  phi0 rubbing angle estimated phistep
1.68d0,0d0,0d0,0d0,0d0  rie-coef
1.54d0,0d0,0d0,0d0,0d0  rio-coefficients
0d-3.45d0  thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0  rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0  rio-coefficients compensator
0d0 0d0  thickness and azimuth for dichroic polarizer
1d0 0d-3 0d-5  Nreal,Nimpar and Nimprp for dichroic polar

layer2.in:
15d0 10000  thickness maximum number of sublayers
0.46364d0 0.52321d0  estimated pitch
0d0 0d0 10d0  phi0 rubbing angle estimated phistep
1.d0,0d0,0d0,0d0,0d0  rie-coef
1.d0,0d0,0d0,0d0,0d0  rio-coefficients
1975d-3.45d0  thickness and azimuth compensator
1.7d0,0d0,0d0,0d0,0d0  rie-coeff compensator
1.5d0,0d0,0d0,0d0,0d0  rio-coefficients compensator
0d0 0d0  thickness and azimuth for dichroic polarizer
1d0 0d-3 0d-5  Nreal,Nimpar and Nimprp for dichroic polar