Modelling of light emission inside planar liquid crystal photonic devices

L. Penninck,[1,2] P. De Visschere,[1,2] J. Beeckman[1,2] and K. Neyts[1,2,*]

1 ELIS (Electronics and Information Systems) Department ,Ghent University, Ghent, Belgium
2 Center for Nano- and Bio-Photonics, Ghent University, Ghent, Belgium

Liquid crystals are widely used to modulate the transmission and reflection of light, but recently they are also being considered as promising light emitting materials. Among new light emitting applications based on liquid crystals we have Organic Light Emitting Diodes, liquid crystal lasers, luminescent solar concentrators,... In many applications the liquid crystal can be approximated as a stack of thin homogeneous anisotropic layers. We present an optical modelling approach for light that is generated inside and emitted from such a stack of liquid crystal layers. The method is based on the plane wave expansion of the dipole field in anisotropic media [1]. The interference and reflection effects caused by the liquid crystal device are modelled using a transfer matrix formalism.

As a first example of our model we study light emission from cholesteric liquid crystals. Dye doped cholesteric liquid crystals are often used to make liquid crystal lasers [2]. The high reflection properties of the planar periodic cholesteric liquid crystal have a strong effect on the spontaneous emission of a dye that is embedded in the liquid crystal. With the developed plane wave simulation model, the spectrum and polarization of the emitted light can be simulated in any direction [3].

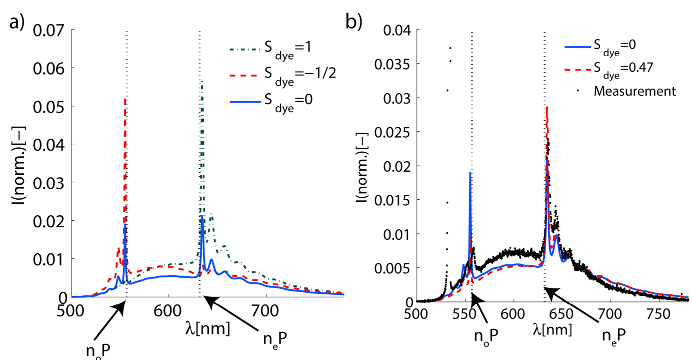

Fig. 1a) Simulated emission of a CLC film for order parameters of the dye molecules in the normal direction. b) Measured and simulated emission of a CLC in the normal direction.

The spectrum emitted by the CLC perpendicular to the cell surface is plotted in Fig. 1.The cholesteric (E7 with chiral dopant BDH1305) film is 6.8µm thick and contains a small amount of dye molecules (DCM). The simulation takes into account the order parameter of the dye in the liquid crystal and is averaged over emission sites across the CLC film. The fluorescence of a CLC is characterized by a photonic bandgap between $\lambda = n_o P$ and $\lambda = n_e P$ with reduced emission. Just outside the bandgap the emission is enhanced in several edge modes. Fig. 1a) shows the simulated spectrum for various order parameters of the dye molecules. When the dye is perfectly parallel ($S_{dye} = 1$) to the director the emission is coupled to the long wavelength bandedge modes. When the dye is perpendicular ($S_{dye} = -1/2$) to the director the emission is coupled to the short wavelength bandedge modes. Randomly oriented dipoles ($S_{dye} = 0$) couple to both sides of the bandgap. The simulated spectrum is compared to the measured spectrum in Fig. 1b). The measurement is in agreement with the simulation when the measured order parameter $S_{dye} = 0.47$ is taken into account.

Fig. 2 compares the measured and simulated emission spectrum under different angles

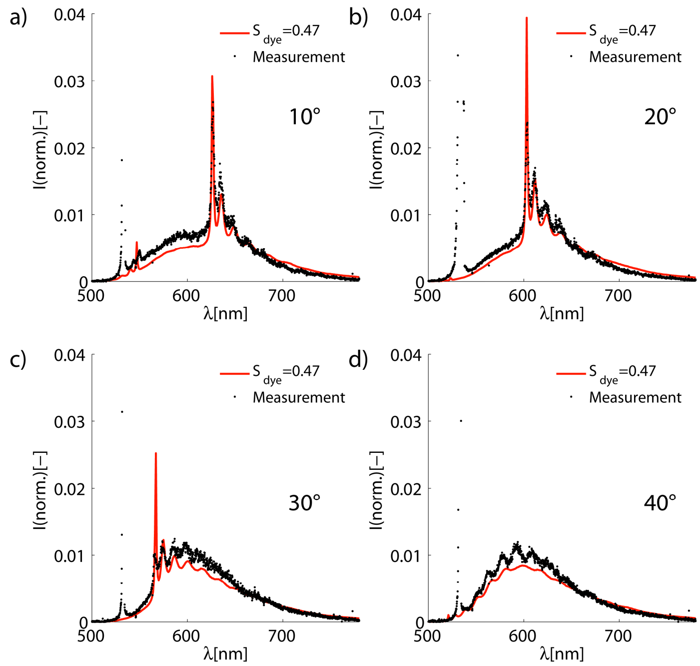

Fig. 2: Measured and simulated fluorescence of dye doped cholesteric liquid crystal under different angles in glass.

The simulated spectrum (solid line) is in good correspondence with the measured spectrum (dots). The spectrum is characterized by a bandgap with reduced emission inside and edge modes at the borders of the bandgap, like for emission in the perpendicular direction. As the angle increases the bandgap shifts towards shorter wavelengths. Eventually the bandgap and the emission spectrum of the dye no longer overlap (Fig. 2d) and the dye spectrum is only modified by small intereference fringes due to the 6.8µm film thickness).

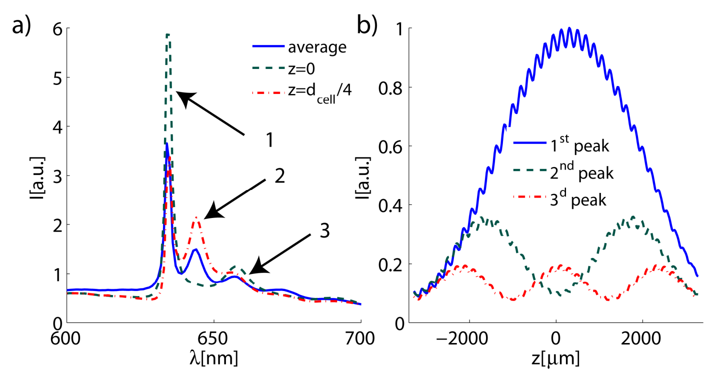

Fig. 3:a) Emission into band edge modes from various positions inside the CLC film. b) Emission into 3 bandedge modes as function of position inside the CLC film. The resonant modes form a standing wave inside the CLC film.

Finally we examine the fluorescence as a function of the position inside the CLC film in Fig. 3. Fig. 3a) show the emission at the long wavelength bandedge for emitters at one quarter ($z = d_{cell} / 4$) and one half ($z = 0$) of the CLC thickness and averaged over all positions. At $z = 0$ light is mainly emitted into two edge modes labelled 1 and 3. At $z = d_{cell} / 4$ the emission is coupled to edgemodes 1, 2 and 3, but comparatively stronger to the second peak. Fig. 3b) show the emission into a single wavelength (top of peaks 1,2 and 3) as a function of the cell position. This picture reflects the intensity profile of the 3 edgemodes since the intensity emitted by a dipole is proportional to the local intensity of a mode [4]. The

edgemodes form standings waves with respectively 1, 2 and 3 maxima inside the CLC.
As a second example of liquid crystal light emitting devices, we simulate liquid crystal slab waveguides. The lay-out of the slab waveguide is depicted in Fig. 4. The structure consists of a glass substrate with a thin emitting layer covered by a 1µm uniform anisotropic slab waveguide (the properties of 5CB were assumed). The LC director is in-plane with layer surfaces. The slab waveguide is bound by an Aluminium layer. The simulations were performed for a randomly oriented dipole antennas at a wave length of $\lambda = 530nm$.

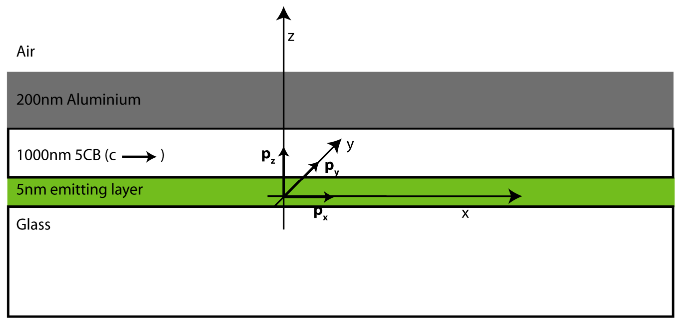

Fig. 4: Simulated liquid crystal slab waveguide.

The ordinary polarized waves emitted by the dipole are plotted in Fig. 5 as a function of the in plane wave vector κ / k_o for different azimuth angles φ. The region of $\kappa / k_0 = 0..n_{glass}$ corresponds to plane waves emitted by the dipole. Minima and maxima are seen in the intensity K^+ of the plane waves, this is caused by interference between plane waves emitted in the glass layer and plane waves reflected by the Al layer. For $\kappa / k_0 = n_{glass}..n_o$ a discrete peak is seen, this is a waveguided mode in the liquid crystal slab. The effective refractive index $\kappa / k_0 = n_{eff}$ of the waveguided modes is found in this way. For $\kappa / k_0 > n_o$ the ordinary waves are evanescent and no more power is emitted (in a loss free medium).

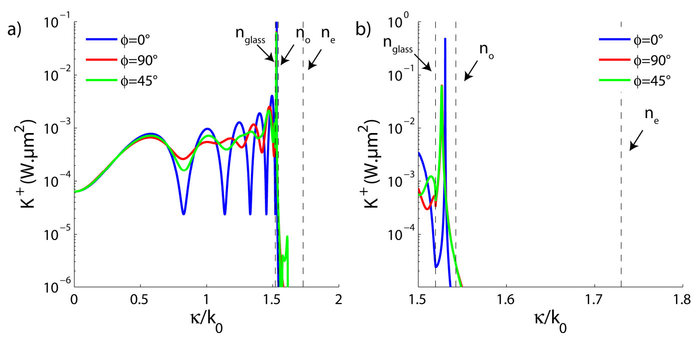

Fig. 5: Emission into ordinary polarized waves for different azimuth. a) Emission in all angles. b) close-up of waveguiding region

In Fig. 6 the emission of extra-ordinary waves is shown. For $\kappa / k_0 = 0..n_{glass}$ a pattern of plane waves is again seen with interference minima and maxima. For $\kappa / k_0 = n_{glass}..n_o$ the coupling to waveguided modes is seen. The important difference between ordinary and extra-ordinary polarization is the occurrence of waveguided modes in the $\kappa / k_0 = n_o..n_e$ region. For waves propagating along the director ($\varphi = 0°$) the extra-ordinary waves experience an effective index of n_o and no emission is seen for $\kappa / k_0 > n_o$. For propagation perpendicular to the director (but still along the surface, $\varphi = 90°$) the extra-ordinary polarization experiences an effective index n_e and waveguided modes are possible up to $\kappa / k_0 = n_e$. For $\varphi = 45°$ the maximum effective index κ / k_0 is in between n_o and n_e.

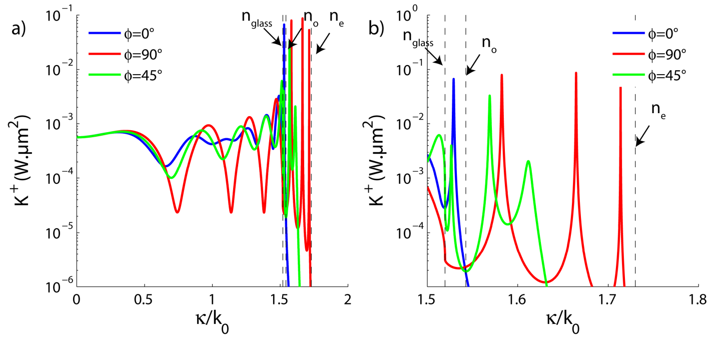

Fig. 6: Emission into extra-ordinary polarized waves for different azimuth. a) Emission in all angles. b) close-up of waveguiding region

References:

[1] L. Penninck, P. De Visschere, J. Beeckman and K. Neyts, *Dipole radiation within one-dimensional anisotropic microcavities: a simulation method*, Optics Express **19**, 18558-18576 (2011).

[2] H. Coles and S. Morris, *Liquid-crystal lasers*, Nature Photonics **4**, 676-685 (2010).

[3] L. Penninck, J. Beeckman, P. De Visschere and K. Neyts, *Light emission from dye-doped cholesteric liquid crystals at oblique angles: Simulation and experiment*, Physical Review E **85**, 041702 (2012).

[4] H. P. Urbach and G. Rikken, *Spontaneous emission from a dielectric slab*, Physical Review A **57**, 3913-3930 (1998).

* presenting author; E-mail: kneyts@elis.ugent.be