Thermal Characterization of the Birefringence of Nematic Liquid Crystals for the Design of Widely-tunable LC-VCSELs

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Abstract—**In this work, the thermo-optical properties of nematic liquid crystals are investigated through localized reflectance spectra measurements performed on a tunable LC-filter. The final aim is to insert such LC in the cavity of a tunable VCSEL device, in which local self-heating due to optical or electrical pumping must be taken into account. We demonstrate that, whereas standard LC E7 is not suited for real device operation, the maximal operating temperature of QYDPLC-36 LC is 95 °C, with a birefringence at 1.55 µm higher than 0.18 at 60 °C.**

I. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) are nowadays key laser sources in the fields of optical communications and sensors. This is due to their numerous advantages related to longitudinal single-mode emission, circular beam shape, low-power consumption and collective fabrication. To further extend their use in new applications such as gas sensing, OCT imaging or miniaturized spectroscopy, wavelength tunability is required. The classical approach to obtain a spectrally-tunable VCSEL is based on the dynamic change of the physical cavity length using a micro electrical-mechanical system (MEMS) [1]. An alternative method is rather to change the refractive index of the cavity. This approach consists of using an intracavity liquid crystal (LC) layer, thus avoiding any moving part in the device. A tunable room temperature continuous wave (CW) lasing was recently reported in an optically-pumped 1.55 µm VCSEL integrating a new kind of LC polymer microcell [2]. However, the tuning range was limited to 23.5 nm, mainly due to the thermal degradation of the standard used LC (E7 from Merck) [3]. In a VCSEL device, the local temperature can typically reach 60 °C due to self-heating under CW pumping. In this work, the optical properties of a LC having better thermal properties than E7, QYDPLC-036 [4], similar to BL-036 from Merck, are characterized using an interference measurement method.

II. Experiments

Many studies have been devoted to liquid crystal refractive index measurements, based on the use of an Abbe refractometer, a spectroscopic ellipsometer or the fabrication of wedge LC cells. Most of them are difficult to implement on birefringent materials or out of the visible range. For these reasons, few data on LC thermo-optical behavior are available in the NIR range. [5]. In this work, a high finesse 1.55 µm tunable optical filter filled with QY-DPLC-036 LC is fabricated and its thermo-optical behavior is studied through localized reflectance measurements. The advantage of this method is the use of a functional device geometry very close to the LC-VCSEL to be designed. It is composed of a LC polymer microcell, a LC alignment grating and two dielectric high reflectivity distributed Bragg reflectors (DBRs) made of 10x(Ti_3O_5/SiO_2) pairs deposited on glass/ITO substrates (Fig. 1). More details on fabrication can be found elsewhere [6].

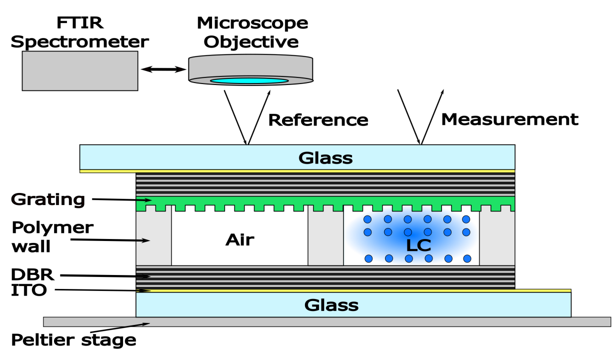

Fig. 1: Cross-section of the fabricated tunable filter including a nanoimprinted grating for LC alignment and schematic of the experimental set-up. After thermal calibration on an empty cell, the thermo-optical measurements are made on a filled microcell.

At room temperature, this device is able to cover a tuning range of 108 nm with only 25 V applied on the ITO electrodes. Here, the applied voltage is kept at 0 V and the temperature is varied instead to mimic a self-heating in the device. To this aim, the filter is placed on a slim Peltier holder inside the microscope stage of a FTIR spectrometer. This way, localized reflectance spectra can be precisely measured on the cell, from room temperature to 85 °C in uniform steps of (5.0 ± 0.1) °C and a non-uniform step close to the clearing temperature. Moreover, measurements are always performed in the same position, which is important because the SU-8 surface is not homogeneous over the whole cell.

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III. Results

The filter resonance positions acquired for both ordinary (o) and extraordinary (e) polarizations as a function of the temperature are plotted in Fig. 2. A red-shift of ordinary modes is observed when the temperature increases, whereas these modes are supposed to remain constant. This is due to the thermal expansion of the polymer layers present in the multilayer stack, namely the 4 µm-thick polymer wall of the LC microcell, and to a much smaller extent, the 500 nm-thick layer used for the LC alignment grating fabrication.

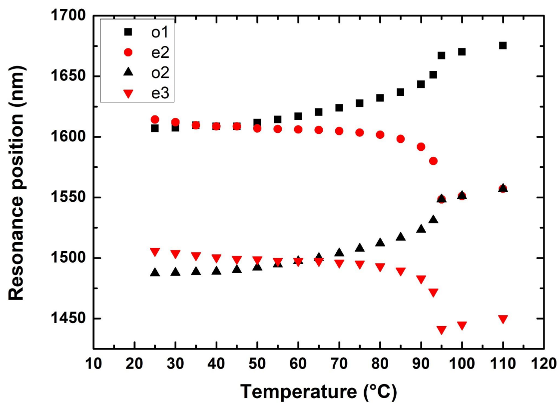

Fig. 2: Spectral positions of ordinary and extraordinary resonance peaks of QYDPLC-036 filter as a function of temperature.

To solve this problem, a reference measurement is also made on an empty cell (Fig. 1). This way, the thermal effects occurring in the whole multilayer stack are differentiated from those taking place in the LC layer only. Once this thermal calibration made, peaks analysis can be performed using a transfer matrix formalism (TMM) and corresponding values of refractive index for both extraordinary and ordinary polarizations n_e and n_o can be extracted from the fitting. The evolution of the average index value $\overline{n} = (2n_o + n_e)/3$ can be also calculated from these data. It identifies a sort of equivalent refractive index as if the material was isotropic. As seen in Fig. 3, the extraordinary index and the average index values decrease with the temperature, whereas the ordinary one remains almost constant. As expected, the birefringence $\Delta n = n_e - n_o$ dramatically falls when the temperature is close to the clearing temperature, which is found to be equal to 95 °C. This has to be compared to the maximal temperature of only 58.5 °C measured on a reference filter filled with QYDPLC-07, a LC very similar to E7 using the same method. Moreover, the birefringence of QYDPLC-036 remains significant at 60 °C (Δn=0.1861). This demonstrates it can be exploited for the design of a widely-tunable LC-VCSEL device.

IV. Conclusions

A simple method for determining the refractive indices of a liquid crystal as a function of the temperature is developed. It is based on localized reflectance measurements performed by FTIR microscopy from 20 °C to 110 °C on a tunable high finesse LC-filter. It gives access to the LC indices values

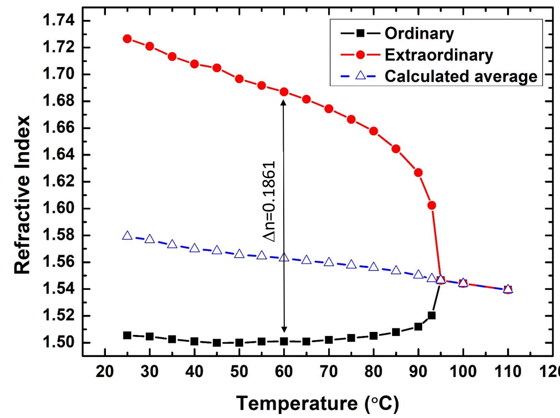

Fig. 3: Refractive indices measured at 1.55 µm for extraordinary (red) and ordinary (black) polarizations as a function of temperature for a QYDPLC-036-based filter. The average index is plotted in blue.

at the filter resonance wavelength (1.55 µm in this work). A birefringence higher than 0.18 at 60 °C is measured for QYDPLC-036, proving this LC is a good candidate for an insertion in a VCSEL. Future work will concern the fabrication of a 1.55 µm widely-tunable LC-VCSEL using this material. A thermo-dependent Cauchy model could be also extracted from these data to get access to index values at other wavelengths and to exploit them in a 3D vectorial opto-thermo-electrical modeling tool (VELM) for the design of a widely tunable 850 nm LC-VCSEL [7].

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