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Optical Design Issues in Electrically Pumped Tunable Liquid-Crystal VCSELs

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***Abstract*—In this work we investigate a tunable 850 nm laser based on a hybrid combination of a liquid crystal micro-cell and a half GaAs VCSEL. The target application is optical coherence tomography. The inherent tolerances of the hybrid technology, the presence of metals in the cavity and the need for a pure extraordinary mode lasing make challenging the optical design of this laser. Hence, VELM, a full 3D and vectorial VCSEL optical solver, is utilized to understand loss mechanisms and provide an optimized design.**

***Index Terms*—Vertical cavity surface emitting lasers, Liquid crystal devices, Semiconductor lasers, Simulation.**

I. INTRODUCTION

Tunable vertical-cavity surface-emitting laser (VCSELs) are very sought after devices for many applications, like sensing. One interesting application is optical coherence tomography (OCT) [1], but also non-medical areas such as quality control [2] can be mentioned. Among the possible configurations, the swept-source OCT [3], based on tunable VCSELs, looks the perfect trade-off between performance and manufacturing costs. Wavelength-Tunable VCSELs are devices where wavelength is tuned by varying the optical length of one of the layers. This can be done by modifying the physical cavity length of an air-gap, as in the tunable micro-electromechanical systems (MEMS) VCSEL [4], or by changing the refractive index of the tuning layer by means of a liquid crystal (LC).

Tunable MEMS VCSELs have been demonstrated at operating wavelengths of 850 nm [5] and 1550 nm [6]. However, MEMS fabrication solution has also some drawbacks such as relatively high driving voltage, when the actuation is electrostatic, and structural weakness due to mobile parts, which additionally make the devices sensible to vibrations, even produced by ambient noise.

The alternative to MEMS fabrication would be to replace the geometrically varying air-gap with a LC reservoir in the tunable VCSEL. In this case, the wavelength tuning is reached by varying the refractive index of the LC layer inside the cavity by applying a moderate driving voltage on it. Very recently, a room-temperature continuous-wave tuning of 23 nm was reported under optical pumping at 1.55 µm [7] for telecom and spectroscopy applications. Key advantages of this technology are good index tuning with moderate applied voltage, low power consumption and no moving part.

However, optical pumping has to be regarded as the preliminary step towards electrically pumped devices, the only ones that provide the compactness and affordability required for mass applications. For this reason a first electrically pumped LC-VCSEL was designed using VENUS [8], a computer-aided software for the 3D full analysis of the VCSELs, starting at first with VELM [9], [10], its vectorial 3D optical solver. In this paper, we describe how the various issues of the optical design have been addressed.

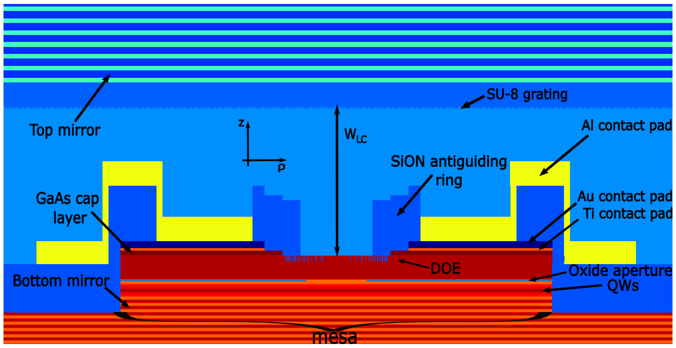

Fig. 1: Sketch of the top-emitting tunable VCSEL highlighting the relevant parts: the mesa, the LC cavity w_{LC}, the QWs, the top (output) and bottom DBRs, the electrode pad to inject current in the active material, the alignment grating, the DOE and the antiguiding structure for mode selection. The color map indicates refractive index values from low (blue) to high (red).

II. METHODOLOGY AND RESULTS

Fig. 1 reports the transverse section of the device; the lower part is an AlGaAs-based half-VCSEL, comprising a 36-pair bottom DBR, index graded for better current transport and three 6 nm GaAs quantum wells embedded in a λ-cavity. Current confinement is achieved by an oxide aperture (6 µm) just above the cavity. On top, a modulation-doped spreading layer is grown for improving current injection, achieved via an annular contact ring (inner size 16 µm), deposited on a highly doped GaAs top layer for good ohmic contact. This layer is removed from the optical path (9 µm radius, 90 nm etching), for its highly absorption would prevent lasing operation. Over this etched area, simulations show that etching a 70 nm thick diffractive optical element [11] helps in reducing the threshold gain, especially at the lower edge of n_E. The LC-reservoir (thickness ranging from 2.5 to 5 µm) separates the active part from the dielectric top-DBR. This is deposited on a glass substrate, starting from a thin ITO layer (45 nm) that guaranties

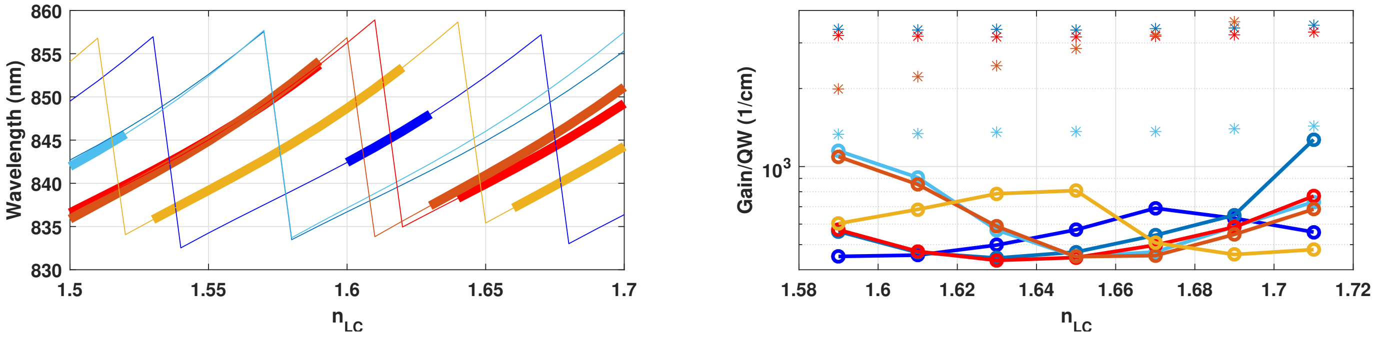

Fig. 2: Output results of the LC-VCSEL VELM simulation varying the SU-8 alignment layer thickness (warm [500 nm] to cold [700 nm] colours) and the LC reservoir (from darker [2800 nm] to lighter [3200 nm] colours). On the left: 1D tuning curves. Thick lines represent the range for which extraordinary emission prevails on the ordinary. On the right: 3D gain thresholds comparison between ordinary (asterisks) and extraordinary modes (line with circle). The y axis has been clamped to put in evidence the details of the extraordinary threshold gain.

the voltage drop on the LC-cell, using a second electrode directly deposited on the half-VCSEL surface. A thin layer of SU-8 photoresist with a grating pattern (200 nm period, 43 nm thick) is fabricated on the 10 pairs top-DBR to allow for correct LC operation and together with polymer side walls enclose the LC in the structure. The extraordinary index (n_E) is oriented as the grating lines, and we refer the mode with the electric field in this direction as the TE mode. In Fig. 1, the TE mode is oriented along the *y* direction (orthogonal to the image). To test the tuning performance of the device, at first a one dimensional simulation is performed, based on a modified TMM approach to rigorously account for the grating layer [10]. In Fig. 2 the emission wavelengths are reported vs. n_E in its variation range of 1.5 to 1.7. The different colours explore the variations inherent to our technology. In fact, both the polymer walls (not shown) and SU-8 thicknesses cannot be controlled better than ±100 nm. The device shows its capability to provide around 25 nm free spectral range. Thresholds are low, ranging 150 to 250 cm^{-1}. The thicker curves correspond to the lasing of the extraordinary mode (E), needed for proper tuning operation. For the different geometrical parameter combinations, large tuning ranges are missed. Therefore tunability is compromised by technological uncertainties, for which an antiguiding design for the ordinary mode (O) is here proposed for the first time. This is based on the observation that n_E variation is larger than needed for a full tuning sweep. The O mode is not guided, while the E mode is guided from just above the refractive index of the dielectric ring (see Fig. 1) with index higher than n_O (around 1.58). This transverse modification provides the results of Fig. 2 (right), which solves the polarization competition inherent to our technology. During the first design, we did not take into account the metal pad, which for LC control motivations is a 500 nm thick Al layer, but just the metal contact ring. Thanks to the experience gained in the investigation of a similar device, though based on an air-gap cavity [11], the tuning channel is a source of power drain, and therefore a way to make the metal more influential than expected on the VCSEL mode. Introducing the full 3D geometry, simulations show a highly increased threshold for the infinitely extended metal pad, compared to the results presented here with a reduced pad of 50 µm compared to the initial choice (120 µm). Reducing the Al contact pad size at the device region will be therefore implemented in a full fabrication process, now already in progress.

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