Modal properties control in Photonic-Crystal Vertical-Cavity Surface-Emitting Lasers

Tomasz Czyszanowski, Maciej Dems
Institute of Physics, Technical University of Lodz
Łódź, Poland
tomasz.czyszanowski@p.lodz.pl

Krassimir Panajotov
Department of Applied Physics and Photonics, Vrije
Universiteit Brussels, Pleinlaan 2, 1050 Brussels, Belgium

Abstract—**We demonstrate the influence of etching precision on the oscillatory behaviour of resonant wavelengths and modal gain of the fundamental and first order transverse mode of photonic-crystal vertical-cavity surface-emitting laser (PhC-VCSEL).**

Keywords: VCSEL, photonic crystals

I. INTRODUCTION

Surface-Emitting Lasers (VCSELs) play a superior role in short-range telecom applications. Their advantages over Edge Emitting Lasers (EELs) manifest themselves in narrow spectral emission, low power consumption and low cost of production since vertical architecture allows on wafer testing. The natural circular shape of the VCSEL beam is conducive to integration with optical fibre systems. The narrow spectral width of VCSEL radiation is assured by the short in comparison to EEL cavity (a half-wavelength or several wavelengths in VCSELs compared to hundreds of wavelengths in EELs) which makes the gain spectrum overlap with only one wavelength corresponding to a single longitudinal VCSEL mode. However, a fully single mode VCSEL operation is only achieved when all but one lateral mode are suppressed. Normally, lasing of the fundamental mode only, defined by a single lobe distribution in a lateral direction is desirable. Such modal distribution best overlaps with the gain radial distribution if carriers are confined to the central part of the VCSEL. That would be achieved if the contacts were placed in the laser axis. Such a design however, would lead to enormous optical losses making impossible laser operation. In real devices the current is injected by contacts that are placed out of the VCSEL axis, far from the regions where the fundamental mode has significant amplitude. Hence, it is necessary to funnel the current into a several micron diameter spot in the center of the active region, which can be assured by selective oxidation [1], proton implantation [2] or structured tunnel junction [3]. The drawback of narrowing the area of current flow is the reduction of the emitted power. On the other hand, broadening of the current aperture favors multimode operation. Hence, additional structuring of VCSELs is necessary to assure their single mode operation for broader current apertures. There have been several approaches to address this issue: antiresonant profile of the refractive index in the distributed Bragg reflector (DBR) [4], surface etching [5], surface grating [6] and photonic crystals (PhC) [7]. The last one is very attractive since it has already proven its ability to select very narrow spectrum of allowed frequencies [8] and discriminate all higher order modes.

The PhC impact on the VCSEL operation has been found to be ambiguous depending on the PhC parameters [9,10]. From one side, the PhC destroys the reflectivity of the DBR mirror, contributing to a strong mode leakage. From another side, it improves the waveguiding and introduces Bragg reflection from the regular net of holes which lead to better mode confinement and hence, to higher efficiency of the stimulated recombination. Only a precise PhC design can balance these two counteracting effects and improve the device efficiency in terms of reduction of the threshold current and increase of lateral mode discrimination. We also found that high precision PhC etching is necessary in PhC VCSELs in order to optimize their modal properties. This is connected with the observed periodicity of the threshold gain with the etching depth Fig. 1 - low threshold appear only for precisely determined depths. The etching depth precision should be better than 0.1 µm in order to achieve threshold gain not higher than 10% over the value

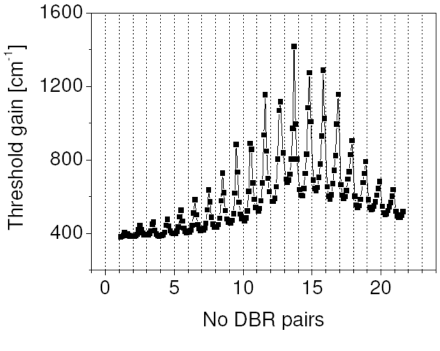

Figure 1. Threshold gain as a function of the PhC number of the etched DBR pairs. The bottom of the holes are assumed to be flat.

expected for the threshold gain minimum within DBR period. Taking also into account the discrimination of higher order modes, which are considered here by the HE_{21} mode, introduces even more stringent limitation, requiring twice higher etching precision.

II. THE RESULTS

In the calculations we use a fully vectorial 3 dimensional optical solver based on the plane wave admittance method [11]. We would like to stress, that analysis performed by the commonly used optical effective models would not resolve the behavior presented here since refractive indices of particular parts of the device are averaged and transformed into uniform blocks defined by constant, effective refractive indices along the axis of the device. In such models, the influence of the PhC is manifested by a waveguide effect only, omitting the leakage and scattering optical losses.

The variations of the emitted wavelength (Fig. 2) and imaginary part of the wavelength which is related to the modal gain (Fig. 3) within a single period of the DBR are governed by the light leakage in the case of shallow etching. It is the most pronounced process when the node of the mode, coincides with the bottom of the PhC holes. An increase in the etching depth increases the light leakage and leads to larger oscillations of the threshold gain within one period of DBR. As the PhC starts to confine the mode, the light leakage is reduced, the oscillations are dumped. Now, the dominant loss mechanisms become diffraction and scattering, which are most pronounced when the antinode of the mode coincides with the bottom of PhC holes. Comparison of Fig. 1 and Fig. 3 shows that rounding of the bottom of photonic crystal which is inherent property of the etching process reduces significantly the oscillations of modal losses. Natural shape of photonic crystal bottoms allows easier control of modal properties of photonic-crystal VCSELs. On the other hand perfectly flat bottom of the holes provides tool assuring extremely strong discrimination of higher order modes.

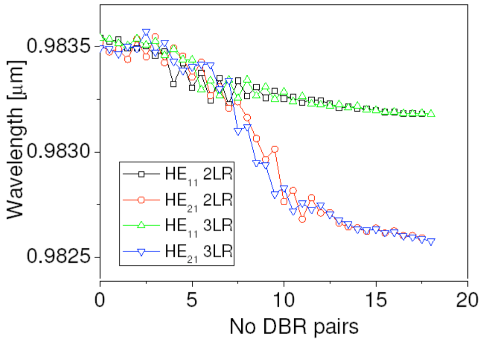

Figure 2. Emitted wavelength of fundamental (HE_{11}) and first order (HE_{21}) modes as a function of the PhC number of the etched DBR pairs. The bottom of the holes are assumed to be rounded, the roundedness is within last two (2LR) and three (3LR) layers.

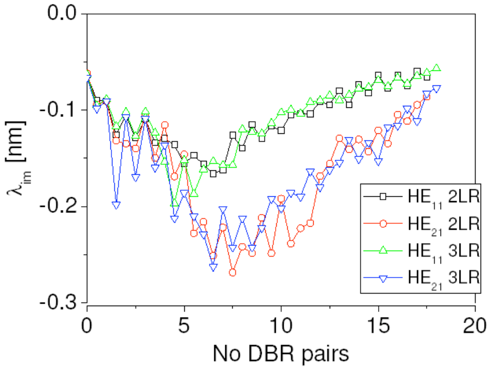

Figure 3. Imaginary part of wavelength of fundamental (HE_{11}) and first order (HE_{21}) modes as a function of the PhC number of the etched DBR pairs. The bottom of the holes are assumed to be rounded, the roundedness is within last two (2LR) and three (3LR) layers.

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