

Study of a novel type of the optical modes in VCSELs

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Abstract. We study novel side-emitting modes in VCSEL microcavities. These modes correspond to π -shaped propagation along the mesa diameter, reflection from angled mesa walls and bottom Bragg reflector. We believe this study of π -modes is important for optimization of VCSEL design for improvement of efficiency.

1. Introduction

Recent progress of the vertical-cavity surface-emitting lasers (VCSELs) has made possible their wide expansion into fiber-optical communication systems, optical input/output devices, transducers and sensors [1,2]. However, further optimization of VCSEL parameters including increase of lasing efficiency and improvement of dynamic characteristics is of high demand for the most of applications mentioned above.

Unfortunately, many VCSEL microcavity configurations support not only the modes of the vertical resonator, but also the disk-propagating modes associated with the circular mesa structure. Such side-emitting light is typically associated with the whispering-gallery modes (WGM) that obviously compromise VCSEL efficiency. However, laser diodes with WGM-operating disk microcavities are very attractive due to the typically high Q-factor and robustness of fabrication [3,4]. Therefore a lot of attention is paid to investigation of the mode structure of the side-emitted light from the VCSEL mesa and study of possibility of WGM generation in VCSEL structures.

Quantum dot (QD) VCSELs with selectively oxidized aperture are the most attractive due to relatively small threshold current (~ 1 mA) and a big expansion of spectral range for device based on GaAs substrate [5]. Threshold current reduction is achieved due to using QD in active region and extremely narrow current aperture, which can be used in consequence to small lateral diffusion of current carriers in QD structures relative to quantum well (QW) structures. But it must be noted that thoughtful optimization of QD VCSELs design is crucial for effective exploitation of their advantages.

2. Experimental samples and study of the side emission from VCSEL microcavity

Our experiments were performed on VCSEL structures grown by MBE on GaAs substrate [1]. Doped top and bottom Bragg mirrors had 20 and 33 pairs GaAs/Al_{0.9}Ga_{0.1}As with gradient composition on boundaries. Active region consisted of 3 QD layers (InGaAs), which were placed in maximum of optical field in undoped optical cavity with composition Al_{0.15}Ga_{0.85}As. Aperture layer p-(AlAs/Al_{0.9}Ga_{0.1}As) was placed in the minimum of the



optical field. Thickness and composition of layers were designed for generation at the wavelength of 980 nm. Mesa structures of 48 μm diameter were manufactured by etching with Ar^+ ion beam. P-doped Bragg mirror was dry-etched with 5% accuracy for investigation of the possibility of WGM generation. Laser generation in VCSEL microcavity could be suppressed by removal of the odd number of quarter-wavelength layers due to decrease of the reflection coefficient.

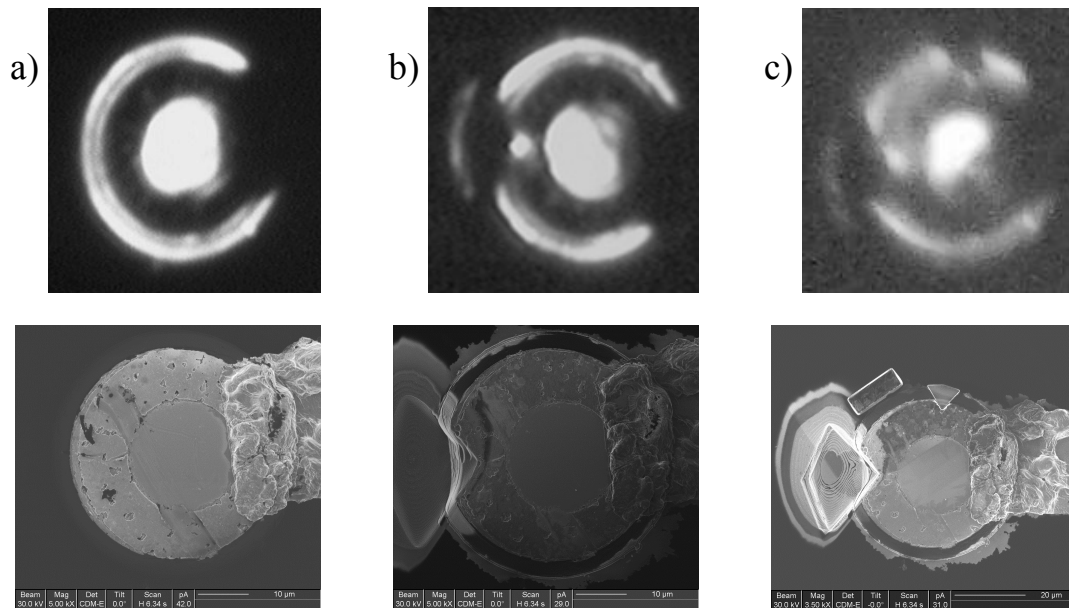


Figure 1 Images of VCSEL near-field near threshold and mesa without etching (a) after focused ion-beam etching of a section (b) and after etching a section and Bragg reflector (c).

Figure 1a shows the typical near-threshold distribution of the near-field of VCSEL with very pronounced emission from the mesa side surface. The spectra of the vertical cavity and of the side-emission are shown in figure 2.

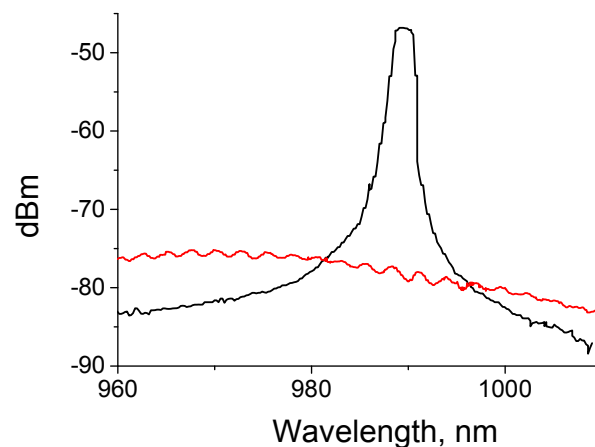


Figure 2 Spatially-resolved spectra of the vertical-cavity and side-emission of VCSEL structure at pump current $I=0.53$ mA.

Spatially resolved spectral measurements were made by 1:1 projection of VCSEL emission with two 30x microscope lenses to the input of the single-mode optical fiber. High-precision positioning of the optical fiber input in the focal plane of the second lens allowed for sampling of the VCSEL near-field with spatial resolution of $\sim 5 \mu\text{m}$ corresponding to the effective diameter of the fiber core. Fiber output was plugged to the optical spectrum analyzer with 90 dB dynamical range at spectral resolution of 0.1 nm. In fig 2, one can clearly see that the spectrum from the mesa center is attributed to the VCSEL cavity with good side-mode suppression of almost 40 dB. In contrast to the vertical-cavity radiation, the emission from the mesa side walls features pronounced ripples corresponding to the mode spacing of 2.7 nm.

3. Theoretical analysis of the spectral mode spacing of the side-emission

First, the cone-shaped microcavity must be considered in order to find the possibility for generation of WGM modes and dependence of the spectral mode spacing of the cone angle and diameter of the mesa. Details of this analysis are published elsewhere [6] and here we only briefly note that no considerable dependence of the WGM spectra on the mesa cone angle can be reported and the spectrum of the cone-shaped mesa can be well approximated with that of the 'classical' disk one of the same diameter. For the high-order WGM mode propagating very close to the outer surface of the circular mesa, the spectral mode spacing can be written as:

$$\Delta\lambda_o = \frac{\lambda^2}{\pi n D} \quad (1)$$

where λ is the emission wavelength, n is the effective refractive index and D is the diameter of the mesa. With $48 \mu\text{m}$ mesa and refractive index of 3.5 one can see the WGM mode spacing is approximately 1.9 nm and does not correspond to the experimental data. However, for the lowest-order WGM modes close to the center of the circular mesa (that can be approximated by triangular propagation) the spectral mode spacing:

$$\Delta\lambda_\Delta = \frac{2\lambda^2}{3\sqrt{3}nD} \quad (2)$$

for the same mesa parameters can be as high as 2.3 nm, much closer to the experimental value.

One should also keep in mind the possibility of generation of the Fabri-Perot modes corresponding to propagation of the light via mesa diameter. However, the spectral mode spacing in such a case:

$$\Delta\lambda_{FP} = \frac{\lambda^2}{2nD} \quad (3)$$

values to approximately 3 nm, higher than in the experiment.

In order to explain the experimental spectral mode spacing, the π -shaped propagation of the microcavity mode was suggested recently [7]. These π -modes propagate along the mesa diameter with reflection from angled mesa walls and the bottom Bragg reflector. Taking the effective thickness of the Bragg reflector L_B into account, one can write the spectral mode spacing of π -modes in the form:

$$\Delta\lambda_\pi = \frac{\lambda^2}{2n(D + 2L_B)} \quad (4)$$

With practical value of $L_B \approx 2\mu\text{m}$, the π -mode spacing according to (4) yields 2.7 nm, which is in perfect agreement with the experiment.

4. Study of the side emission from the modified VCSEL microcavity

In this section we describe the measurements that were carried out in order to suppress emission of the side-mode of the microcavity and to reveal its origin experimentally. In order to verify the possibility of WGM generation, we prepared a cavity with a section removed from the circular mesa structure (Figure 1b). This was done by focused ion beam etching with the Strata FIB 205 setup [8]. With WGM nature of VCSEL side-emission, one should expect suppression of fringes seen in its spectrum in Figure 2. However, neither the measured near field distribution shown significant changes (figure 1b), nor the fringes disappeared in the spectrum of the side-emission as can be seen in the spectra at 12 and 1 o'clock in Figure 3.

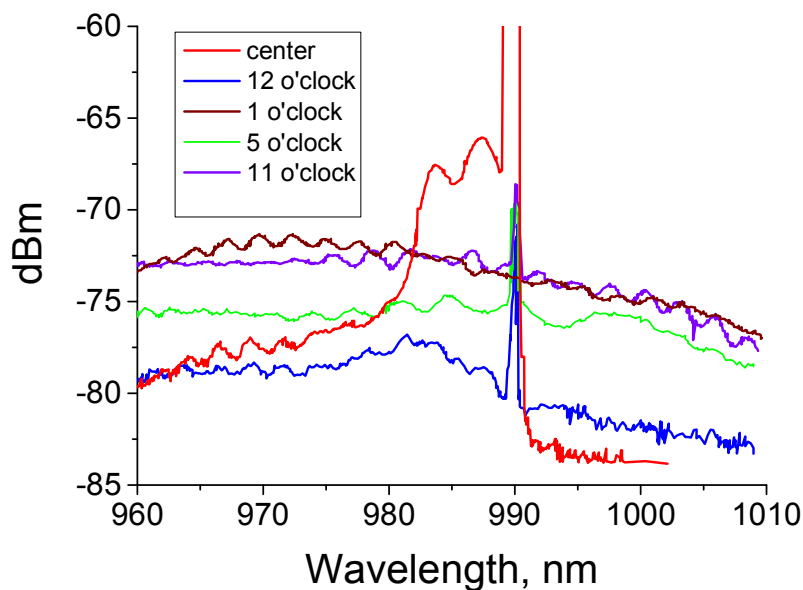


Figure 3 Spatially-resolved spectra of emission from different parts of etched VCSEL mesa. Red line corresponds to the vertical-cavity mode (emission from the mesa center). All other lines correspond to the side-emission from different parts of the etched mesa (Figure 1c): blue line – 12 o'clock; brown line – 1 o'clock; green line – 5 o'clock; purple line – 11 o'clock.

In order to experiment with the π -shaped propagation of the mode over the VCSEL cavity, we performed additional processing of the experimental samples. We made angled etching of the bottom Bragg reflector under the mesa as shown in Figure 4 in order to suppress the generation of π -modes. The detailed scheme of the bottom Bragg reflector etching is shown in figure 4. This angled etching was located in such a way to enable measurement of emission from the opposite side of the mesa circle. The near field of VECSEL structure with such sophisticated etching is shown in figure 1c.

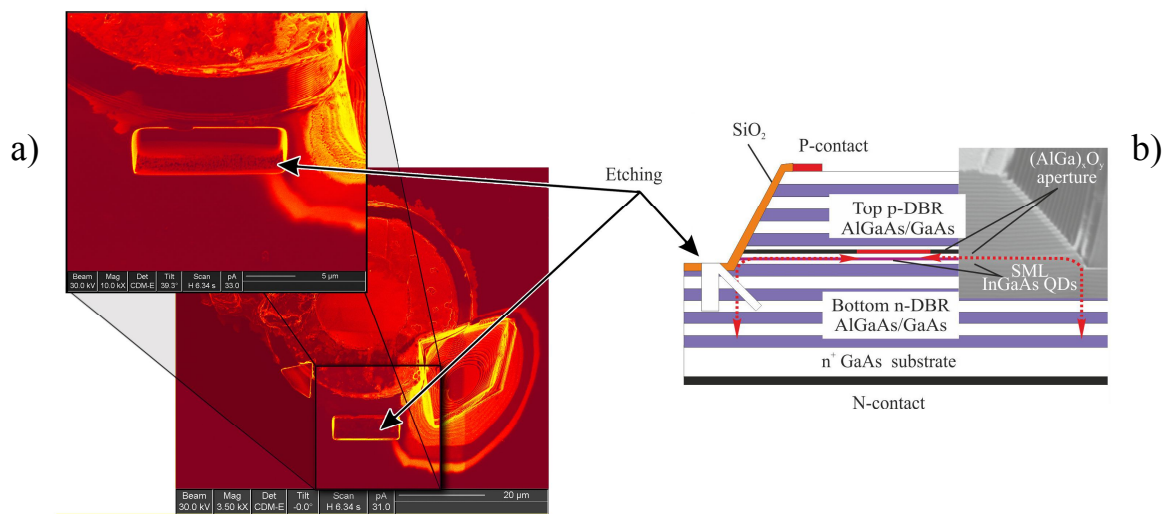


Figure 4 VCSEL with etched mesa and bottom Bragg reflector (a) and π -shaped light propagation in VCSEL cavity with angled mesa walls (b).

From the spectra at 11 and 5 o'clock in figure 3 one can see that not only did the etching of the Bragg reflector suppress the fringes in the spectrum measured at the point of etching (11 o'clock corresponding to figure 1c), but also the opposite side of the mesa circle (5 o'clock corresponding to figure 1c) featured absence of the π -mode signature in the side-emission spectrum around 970 nm.

5. Conclusion

In summary, we have demonstrated and studied the novel side-emitting modes in VCSEL microcavities. These modes correspond to π -shaped propagation of radiation along the mesa diameter with subsequent reflections from angled mesa walls and bottom Bragg reflector. Excitation of these modes should be taken into account for optimization of VCSEL microcavities for improvement of efficiency.

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