High-Order-Mode VCSEL With 12 mW Output Power

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We report high-power single-higher-order transverse mode emission of a large-area oxide-confined rectangular-shaped VCSEL with a multi-spot shallow surface relief. Both a record-high output power of 12 mW and a record-low differential series resistance of 18 ohms are achieved. Stable single-higher-order transverse mode emission with a side-mode suppression ratio exceeding 35 dB is maintained up to thermal rollover. Measurements of near- and far-field intensity profiles of the higher-order mode are presented.

1. Introduction

The special features of VCSELs such as low power consumption, circular beam shape, emission perpendicular to the wafer surface, on-wafer testing before packaging, and efficient high-frequency modulation are providing the motivation for a continued search for new device types. Besides, VCSELs are ideally suited to form two-dimensional arrays of compact optical sources owing to their low threshold currents and high packing density. These attributes make VCSELs attractive light sources for various applications such as optical data transmission [1], optical navigation with computer mice [2], gas sensing [3], optical illumination and pumping [4], or optical particle manipulation [5]. However, VCSELs normally operate in multiple transverse modes, due to the large transverse dimensions of the device. Many VCSEL applications, on the other hand, require high-power single transverse mode emission. Hence, much effort has been invested in the research into such single-mode VCSELs.

For this aim, we contribute with a VCSEL type that has a rectangular aperture with large aspect ratio and provides high single-mode power using a shallow etching technique. In this technique, a quarter-wavelength antiphase layer is added onto a regular top Bragg reflectors in order to induce a decrease in top mirror reflectivity. This layer is then selectively removed during processing by means of wet-chemical etching, such that the threshold gain of a desired mode is lower than that of all other transverse modes. The oscillating laser mode has a high transverse mode order. The emitted laser wavelength is around 850 nm. As an additional favorable feature, the devices show low differential series resistances due to the large aperture area compared with usual single transverse mode VCSELs.

2. Description of the Device

Figure 1 shows a schematic (top) and a top view (bottom) of an 8-spot surface-etched rectangular-shaped VCSEL to enforce single-mode operation of the E_{81} mode having 8 maxima along the aperture length and one maximum along the aperture width. The epitaxial material was provided by Philips Technologie GmbH U-L-M Photonics. The layer structure consists of a bottom n-doped 37 pairs distributed Bragg reflector (DBR), a one-wavelength thick cavity containing three 8 nm thick GaAs quantum wells separated by 10 nm AlGaAs barriers, a 22 pairs p-DBR and a topmost quarter-wave thick GaAs antiphase layer, all grown on an n-GaAs substrate.

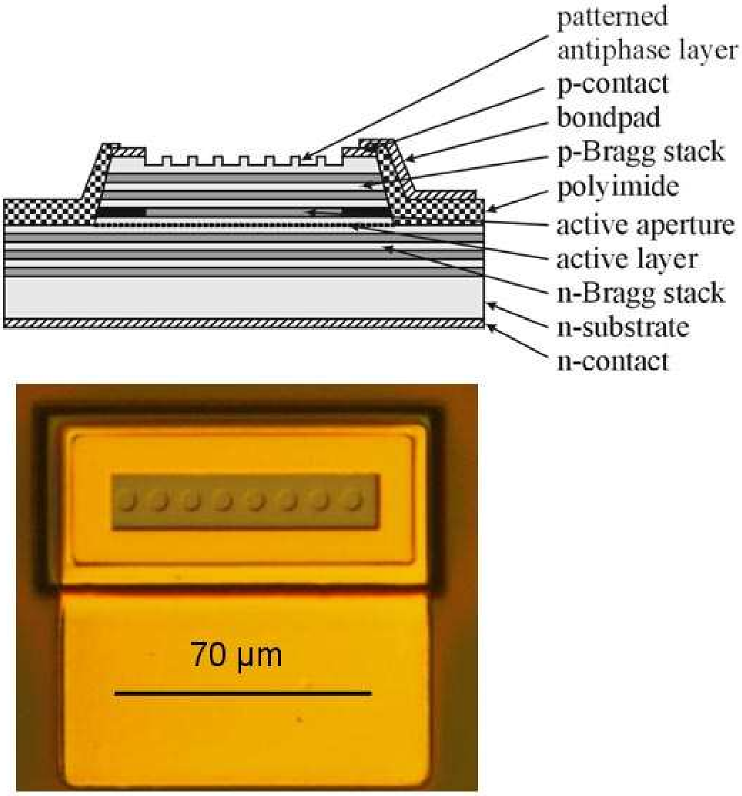

Fig. 1: Schematic drawing (top) and top view (bottom) of a fully-processed 8-spot shallow surface etched rectangular-shaped VCSEL.

The cavity resonance is in the vicinity of 850 nm. The antiphase layer induces losses for the total structure. This layer is selectively removed in a single processing step using wet-chemical etching. The 8-spot shallow etch pattern in Fig. 1 is adapted to the intensity profile of the E_{81} mode. The diameter of each spot is about 6 µm, the pitch is 9 µm and the active aperture area is about 6 µm × 68 µm. The pattern is designed such that there is a maximum overlap between the etched spots and the calculated intensity maxima of the targeted mode. With this method, a single-higher-order transverse mode is selected. The analysis of higher-order-mode selection using surface etching was reported in [6]. Current confinement is achieved through thermal oxidation of an AlAs layer placed just above the one-wavelength thick inner cavity. This step defines the aperture area mentioned above.

Wet etching is used to reach the AlAs layer. N- and p-type metalization processes are applied, followed by polyimide passivation. Finally, bondpad metalization is carried out for electrical contacting.

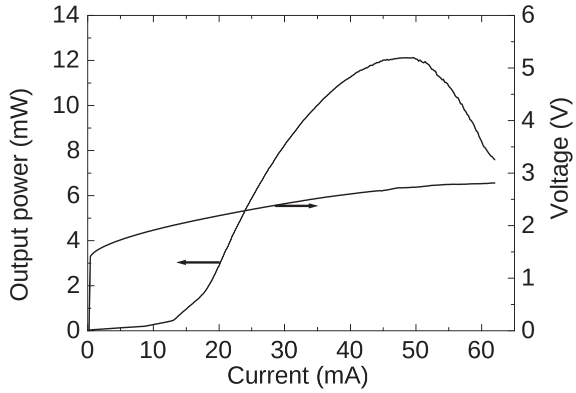

Fig. 2: CW operation characteristics of an 8-spot surface-relief VCSEL with an active aperture area of $6.3 \times 68.3\,\mu m^2$.

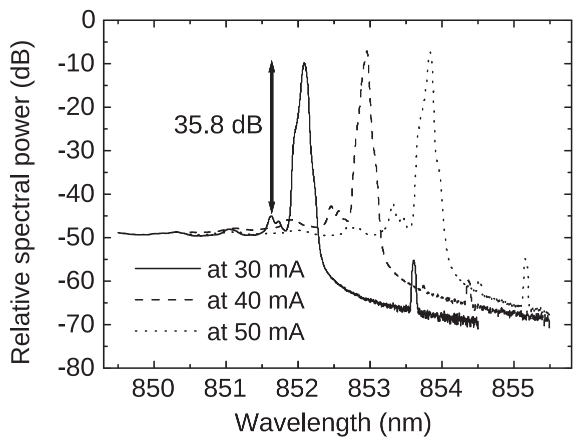

Fig. 3: Emission spectra of the device in Fig. 2 at different currents.

3. Characterization and Results

Room-temperature continuous-wave light–current–voltage (LIV) characteristics of the device from Fig. 1 are shown in Fig. 2. The corresponding spectra at different currents are depicted in Fig. 3. The competitive mode is about 35 dB lower than the targeted mode even up to thermal rollover. The maximum output power at thermal rollover is 12 mW, which is a record-high output power for fully monolithic VCSELs, either oscillating on the fundamental mode [7]– [15] or on higher-order modes [16], [17]. The average differential series resistance is 18 Ω, as obtained from the slope of the current–voltage curve in the range from 20 to 50 mA, which is remarkably low. The threshold current is 12.8 mA and the maximum differential quantum efficiency is 38.5 %. The relatively high threshold is due to optical losses induced by the antiphase layer.

In order to identify the main modes in the spectra in Fig. 3, we have performed spectrally resolved near-field measurements by scanning a lensed fiber tip over the output aperture with high resolution. Figure 4 shows the near-field intensity profile of the same VCSEL at 30 mA, taken with a spectral width of 0.046 nm centered around the spectral peak in Fig. 3 (no changes are observed even with 5 nm spectral width). In contrast to the simulations,

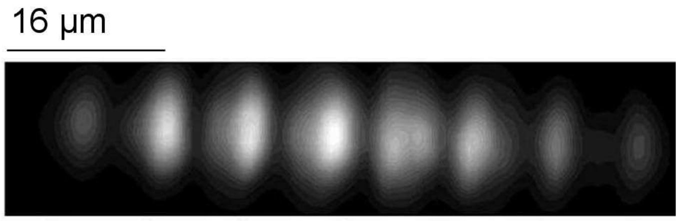

Fig. 4: Near-field intensity profile of the device in Fig. 2 at 30 mA.

there is a marked difference between the intensity maxima and shape of the spots. We attribute this to the inhomogeneous temperature throughout the active aperture, which leads to cavity detuning. Figure 5 shows the measured far-field intensity in the plane defined by the etch spots. Four major peaks are observed. The peak positions correspond well with model calculations assuming diffraction from a multi-spot phase grating, where the distance between spots and the phase shift of $\pi/2$ between etched and unetched regions are the main parameters.

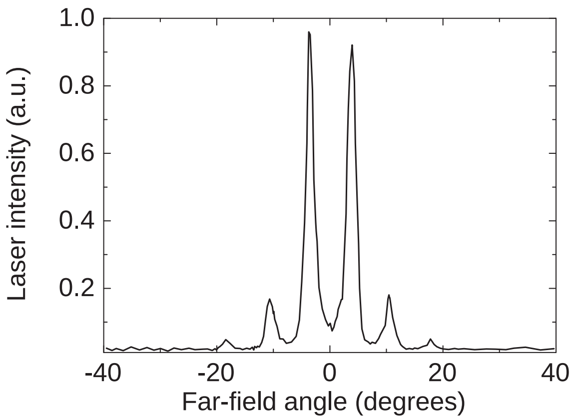

Fig. 5: Measured far-field intensity profile corresponding to Fig. 4.

4. Conclusion

We have demonstrated that large-area ($> 400\,\mu\text{m}^2$) multi-spot surface-etched rectangular-shaped VCSELs show stable high-power single-higher-order transverse mode emission. Moreover, the differential series resistance is low. Near- and far-field intensity profiles prove the successful mode selection. The manufacturing of this VCSEL needs only one additional lithography and etching step, which makes it attractive for commercial fabrication. The VCSELs are intended to be applied for optical manipulation of microparticles.

When positioned at an angle with respect to the fluidic flow direction underneath a microfluidic chip, all-optical deflection of flowing particles can be achieved with light forces. Non-mechanical sorting is thus possible [5]. With the VCSEL presented here, the distance between the intensity spots is 9 µm, which cannot be easily achieved with conventional linear VCSEL arrays as applied in [5].

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