Improving Single-Mode VCSEL Performance by Introducing a Long Monolithic Cavity

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We report on the improvement of several selectively oxidized VCSEL characteristics by introducing a long monolithic cavity. The samples compared are grown with various cavity lengths using solid-source MBE. The 980 nm-regime is chosen as emission wavelength to facilitate growth by using binary GaAs cavity spacers. A record high single-transverse mode output power of 5 mW at a series resistance of 98 Ω is obtained for a 7 μm aperture device with a 4 μm cavity spacer. Using an 8 μm cavity spacer, devices up to 16 μm aperture diameter emit 1.7 mW of single-mode power with a FWHM far-field angle below 3.8°.

1. Introduction

Single-mode operation in longitudinal as well as transverse direction is one of the most distinguished advantages of the vertical-cavity surface emitting laser (VCSEL). Applications for single-mode VCSELs range from Gbit/s data transmission [1] and storage over chemical analysis [2] to medical applications [3]. While longitudinal single-mode operation is inherent to the short cavity design of VCSELs, transverse mode behavior depends strongly on layer structure and device size. To date, the single-mode VCSELs with the largest lateral dimensions use proton-implanted designs [4],[5]. Selectively oxidized VCSELs offer much improved electrical and optical properties [6], except for the fact that the increased optical guiding requires much smaller aperture diameters for single-mode operation. However, small apertures cause increased series and thermal resistances, may affect device lifetime, and make mass production difficult due to tight aperture tolerances. It has already been shown that a long monolithic cavity can significantly reduce the far field angle [7]. We present the improvement of various VCSEL characteristics such as increased single-mode output power and increased-area single-mode operation due to increased diffraction losses for higher-order transverse modes and improved thermal resistance by using a long monolithic cavity.

2. Light-Current Characteristics and Transverse Mode Behavior

Fig. 1 shows a comparison of the light-current characteristics of 7 μm-aperture selectively oxidized VCSELs with 0, 2, 4, and 8 μm cavity spacers, respectively. The 0-spacer structure corresponds to our standard VCSEL structure with In_{0.15}Ga_{0.85}As-quantum wells, emitting at 975 nm, as described e.g. in [8]. The GaAs cavity spacers are incorporated between the active region...
Fig. 1. Light-current and voltage-current characteristics for 7 µm-aperture devices with cavity spacer lengths 0, 2, 4 and 8 µm. Single-transverse mode operation ranges are indicated by the marked data points. The inset depicts the general VCSEL structure.

and the n-type mirror as depicted in the inset of Fig. 1, allowing to obtain low resistance even for low doping levels which minimize absorption. It is seen that for cavity spacer lengths below 8 µm, the general characteristics are very similar, although there appears to be a continuous decrease in output power with increasing spacer length. For the 8 µm spacer device, threshold current is significantly increased and the general form of the curve is distorted. The increase of threshold current can be attributed to increased diffraction losses that now concern not only higher-order transverse modes but also the fundamental transverse mode. The kink between about 6 and 6.5 mA is caused by longitudinal mode switching. Smaller bumps can be attributed to transverse mode changes. Even though the cavity spacer layer is only lightly doped, series resistance shows no significant increase with increasing cavity length. For the following spectra measurements, a spectrum analyzer with a maximum resolution of 0.1 nm is used; maximum single-mode output is determined by 30 dB side-mode suppression ratio (SMSR). Maximum single-transverse mode operation conditions also indicated in Fig. 1 by the marked data points reveal that the 8 µm-spacer device possesses the largest transverse single-mode current range but exhibits longitudinal mode switching as mentioned before. The 4 µm-spacer device, however, oscillates on one longitudinal and transverse mode up to a current of 9 mA and therefore exhibits the largest single-mode output power. The maximum value of 5 mW is to our knowledge the highest single-mode VCSEL output power reported to date. Additionally, since this device is significantly larger than conventional single-mode devices, the series resistance of 98 Ω is the lowest value measured for such a high single-mode output power.

Fig. 2 shows spectra for this device for various driving currents, revealing that the first higher-
order mode is suppressed below measurement capabilities, meaning well below 30 dB up to a current of 9 mA. Here, one of the main advantages of the cavity spacer becomes apparent: due to the increased diffraction losses of higher order modes, caused by their larger diffraction angle, the single-mode current range of standard VCSELs can be increased significantly. Whereas standard devices exhibit multi-mode emission already at threshold for aperture diameters exceeding about 6 \(\mu\)m, even 16 \(\mu\)m-aperture devices have shown a significant single-mode current range for the 8 \(\mu\)m cavity spacer sample. Since these large devices possess a very small transverse mode spacing, single-mode operation cannot be easily derived from common spectra measurements anymore. Single-mode emission is therefore determined by recording the far field profile, yielding a maximum distinguishable SMSR of about 20 dB (see section 3.).

3. Far-Field Measurements

In addition to standard characterization and spectra measurements, the different samples are also analyzed using near-field and far-field profile analysis. The scanning near-field analysis clearly shows that index guiding decreases with increasing cavity spacer length. Also, the additional longitudinal modes show significantly increased guiding as expected from the standing wave patterns. Apart from identifying individual transverse modes, measurement of the far-field full-width half-maximum (FWHM) angle versus device current can also serve as a means to determine transverse single-mode emission, especially for larger devices where transverse mode spacing is too small to be clearly distinguished in spectra. Fig. 3 shows the far-field FWHM angle for different devices of about 12 \(\mu\)m aperture as a function of current. The reference device without cavity spacer represented by the filled squares exhibits a large angle already at threshold, which increases strongly with current, indicating transverse multi-mode emission. For devices with cavity spacers, the angle remains almost constant for a certain current range, until it increases abruptly. Comparing this to spectra measurements on smaller devices, it is found that this kink occurs at about 20 dB SMSR. Therefore, using long enough cavity spacers serves to increase the transverse single-mode range of large devices as well. Using this approach, we have found devices with up to 16 \(\mu\)m apertures emitting 1.7 mW of single-mode output power with a FWHM far-field angle of below 3.8 °.

Assuming a Gaussian index distribution in the VCSEL, the far-field angles can be normalized using the square root of the aperture diameter. This results in a layer structure specific diffraction angle independent of device size. When comparing these normalized far-field angles for the different device structures, it is found that the length of the cavity spacer is of no significant influence. Therefore, the long monolithic cavity itself does not influence the far field angle but is just responsible for the fact that larger area single-mode devices can be obtained which show low-divergence angle emission [7].

The normalized thermal resistance, on the other hand, decreases continually with increasing cavity spacer length, namely by a factor of 2 from 1.50 Kcm/W for a 0 \(\mu\)m spacer to 0.78 Kcm/W for a 8 \(\mu\)m spacer. This indicates that the additional homostructure of the cavity spacer effectively acts as a heat spreading layer which reduces the amount of heat accumulated in the active area.
Fig. 3. FWHM far-field angle versus current for 12 µm aperture devices from all four samples of 0, 2, 4, and 8 µm spacer length. Single-mode emission with a SMSR of about 20 dB is characterized by the sudden increase of far-field angle. The inset shows the measured far-field cross-sections of the 8 µm-spacer device for currents of 10, 17, and 33 mA, corresponding to the three lowest-order modes.

4. Conclusions

We have successfully fabricated long monolithic cavity VCSELs in the 980 nm wavelength regime using n-GaAs cavity spacers of various lengths. The devices reveal significant improvements in transverse single-mode behavior and thermal resistance as a result of the increased cavity length. The far field angle is significantly reduced by realizing increased-area single-mode devices. A record single-mode output power of 5 mW is achieved for an exceptionally large device of 7 µm aperture diameter, resulting in a low series resistance of 98 Ω. A quick means of determining single-mode emission from far-field measurements with a SMSR of about 20 dB is presented, which allows to determine single-mode ranges even for large diameter devices. Longitudinal modes are observed for certain mismatch conditions of cavity resonance and gain peak, therefore providing the possibility to control them by adjusting mismatch accordingly.

References

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