Improved Output Performance of High-Power VCSELs

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This paper reports on state-of-the-art single device high-power vertical-cavity surface-emitting laser diodes (VCSELs). The laser diodes are studied in terms of electro-optical characteristics, beam performance and scaling behavior. The maximum cw output power at room temperature of large-area bottom-emitting devices with active diameters up to 320 μm is as high as 0.89 W which is to our knowledge the highest value reported for a single device. Measurements under pulsed conditions show more than 10 W optical peak output power.

1. Introduction

Small diameter VCSELs are accepted devices for datacom applications due to their distinguished performance. One of those is the high conversion efficiency of more than 40 % which is also a basic for high-power devices. But most of the datacom VCSELs have output powers in the range of a few mW. For higher powers edge-emitting lasers are more suited because they achieve up to several W at high conversion efficiencies [1, 2]. Disadvantages of these devices are the strongly elliptical beam with a large divergent far-field angle in the fast axis and the high effort in testing and mounting. To close the gap between low power datacom VCSELs and high power edge-emitting lasers large-area single device VCSELs [3] have been investigated. Our aim is to fabricate devices which combine high optical output powers in the Watt regime and high conversion efficiencies above 20 % in cw-operation at room temperature. As carried out in this previous work [4, 5], large-area top-emitting VCSELs are not suited because of the decreasing efficiencies with increasing device size and the poor beam quality due to the ring-shaped near field caused by the inhomogeneous carrier injection through the top ring contact. Therefore we have concentrated the work on bottom-emitting devices which provide a homogeneous current injection also for large-area devices and are suited for a sophisticated mounting technique.

2. Device Structure

The layer structure is grown by solid-source molecular beam epitaxy on GaAs substrate. A schematic cross-sectional view of a VCSEL array is shown in Fig. 1. The Carbon doped p-type Bragg reflector consists of 30 pairs of $Al_{0.9}Ga_{0.1}As$/GaAs layers. The active region is composed of three 8 nm thick $In_{0.2}Ga_{0.8}As$ quantum wells for an emission wavelength of about 980 nm. Above the p-type cladding layer a 30 nm thick AlAs layer is inserted. Wet chemical etching with Sulphuric acid is used to define mesa type active regions. The exposed AlAs layer is laterally oxidized in a water vapor atmosphere using Nitrogen as carrier gas at a temperature of 410°C in order to form the current aperture and determine the active diameter of the device. For light emission through the GaAs substrate the Silicon doped n-type distributed Bragg reflector has only 20 layer pairs of the same composition as the p-type mirror. On top of the mesa a full size p-contact consisting of Ti/Pt/Au is evaporated which provides a homogeneous current distribution and serves as a wettable metal pad for soldering. After mechanically polishing the GaAs substrate down to a thickness of 150 μm, an anti-reflection coating of Si_3N_4 with refractive index of 1.89 and quarter-wavelength thickness is deposited using plasma enhanced chemical vapor deposition. The Si_3N_4 layer is opened selectively with reactive ion etching for evaporating Ge/Au/Ni/Au large-area contacts surrounding the emission windows. After annealing the n-type contact at 400°C the processing is completed by depositing an electroplated Au layer of 1–2 μm thickness.

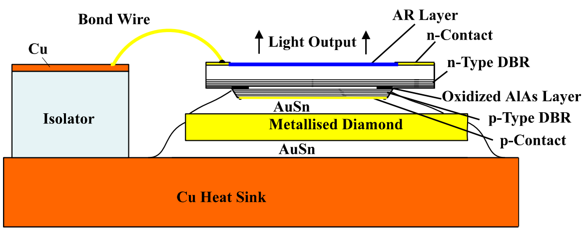

Fig. 1. Cross-sectional view of the oxidized VCSEL array.

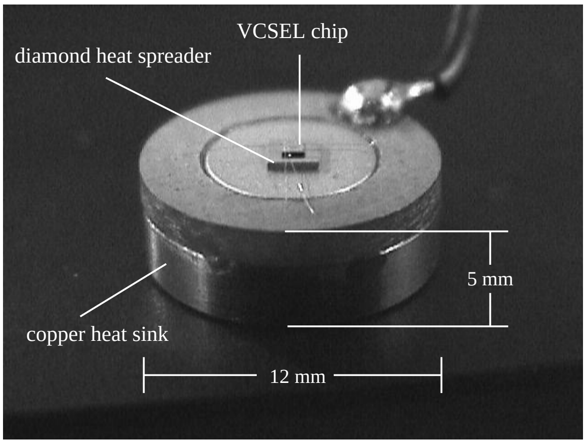

Fig. 2. Mounted semiconductor chip on metalized Diamond and Copper heat sink.

3. Mounting on Heat Sinks

VCSELs with active diameters up to 100 μm can be operated without mounting on heat sinks and are generally capable for on-wafer-testing of electro-optical device performance like threshold current density, threshold voltage, differential resistance, differential efficiency and emission wavelength. Due to a slight gradient in layer thickness across the grown wafer and corresponding detuning of gain and cavity resonance, device performance depends on wafer position. Only large active diameter VCSELs with matched gain and cavity resonance are suited for highest output powers since not optimized detuning increases threshold current and dissipated power and thus device heating drastically.

On-wafer tests are performed in order to select appropriate large-area devices or arrays for mounting. The standard mounting technique is shown in Fig. 2. The cleaved semiconductor chip with dimensions of $0.5\times0.5\,\mathrm{mm}^2$ is soldered junction-down with eutectic $Au_{80}Sn_{20}$-solder on a metalized diamond heat spreader of $2\times2\,\mathrm{mm}^2$ size. The same AuSn solder is used to attach the Diamond on a small Copper heat sink. Soldering is achieved in a single-step heating process at a temperature of about 300°C. The cylindrical Copper mount has a diameter of 12 mm and a height of 5 mm. In the backside a thread is cut for easy mounting on a larger heat sink. Heat dissipation predominantly occurs through the p-type contact. Mounting can be done automatically by pick-and-place machines because alignment tolerances are much more relaxed compared to edge-emitting lasers. Electrical connections are achieved using wire-bonding.

4. Output Characteristics

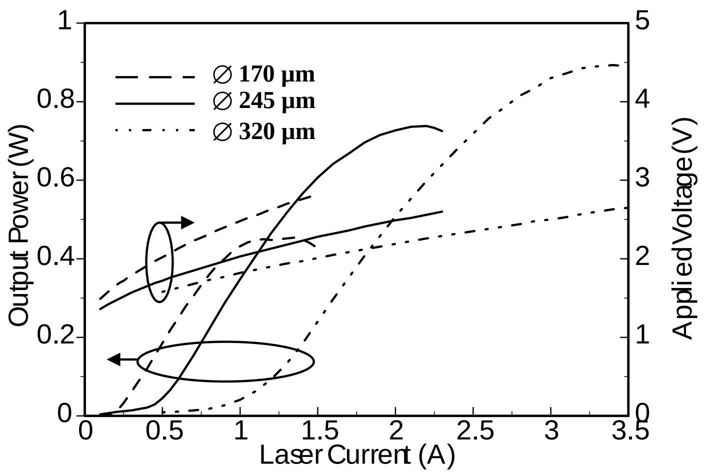

Fig. 3. Output characteristics for large-area single devices with 170, 245, and 320 μm active diameter.

Fig. 3 shows the output characteristics for 3 different device sizes of 170, 245, and 320 μm. The threshold currents are 215 mA, 465 mA, and 1.1 A, respectively, corresponding to a threshold current density of 1 kA/cm^2. The maximum output powers are 450 mW, 740 mW, and 890 mW which are to be compared with 350 mW for a device of 200 μm active diameter reported earlier [6]. Progress is mainly due to improved mounting and soldering techniques.

Various applications like free space data transmission, optical sensing or Light Detecting And Ranging (LIDAR) request pulsed operation. Therefore, we have investigated dynamic behavior. Fig. 4 shows time resolved output power characteristics for excitation with electrical pulses of approximately 10 ns width and a 67 kHz repetition rate where impedance matching of electrical supply lines was not yet optimized. The maximum peak output power of 10 W is achieved at a current of 14 A which was the limit of the current source used. Fig. 5 compares cw and pulsed operation. Obviously, thermal roll-over limits the cw maximum output power whereas pulsed power shows a linear increase with driving current up to 14 A corresponding to a current density of 17.5 kA/cm^2.

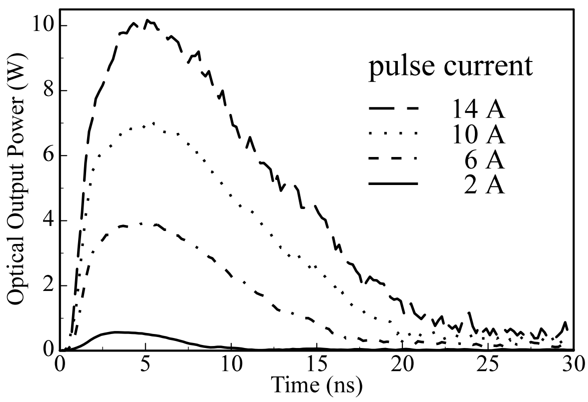

Fig. 4. Optical pulses measured by a fast photodiode at different laser currents. The width of the electrical pulses was about 10 ns and the repetition rate 67 kHz.

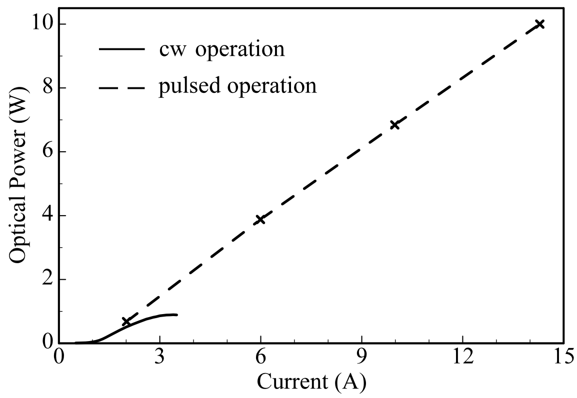

Fig. 5. Comparison of cw operation (solid line) with 0.89 W maximum optical output power and pulsed operation (dashed line) with 10 W maximum peak power.

Due to the large VCSEL diameter the emitted light is strongly multi-mode. For spectral measurements care has to be taken that all light is fed into the spectrum analyzer. For light coupling we have used a 600 μm core diameter Silica fiber with 0.37 numerical aperture at the expense of a resulting comparatively low spectral resolution of about 0.5 nm. Fig. 6 shows measured spectra where individual transverse modes are not resolved. The

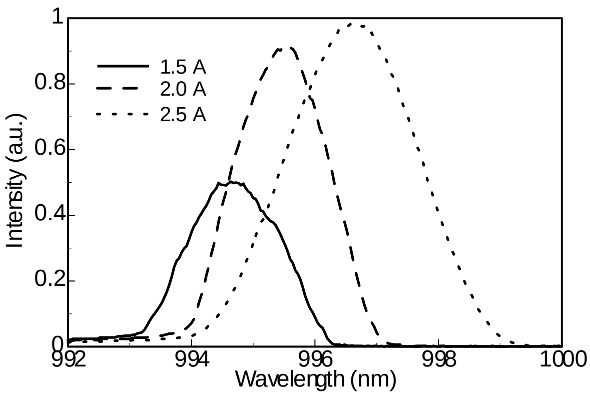

Fig. 6. Spectra of the 320 μm active diameter device for different laser currents.

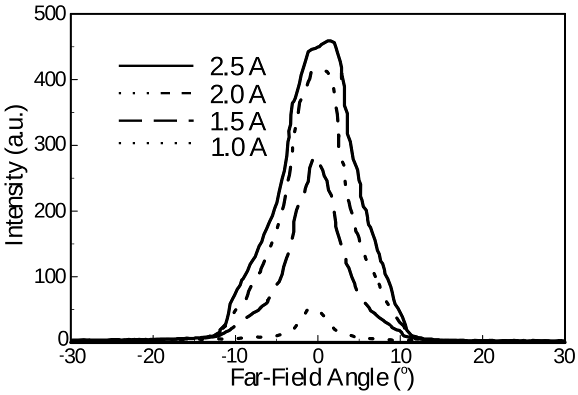

Fig. 7. Far-field profiles of the 320 μm active diameter device for different laser currents.

peak wavelength is in the range of 995 nm due to the cavity resonance but devices can easily be designed for emission wavelengths between 940 nm and 1020 nm. The full width at half-maximum (FWHM) of the spectra is smaller than 5 nm for all currents which is attractive for applications like pumping of Er- or Yb-doped fibers and Nd-YAG microdisk lasers.

The cw far-field patterns of the laser studied are shown in Fig. 7 for different excitation currents. The graphs show a single lobe with less than 12° FWHM for all currents. No side-lobes or amplified spontaneous emission are observed. Due to the circularly symmet-

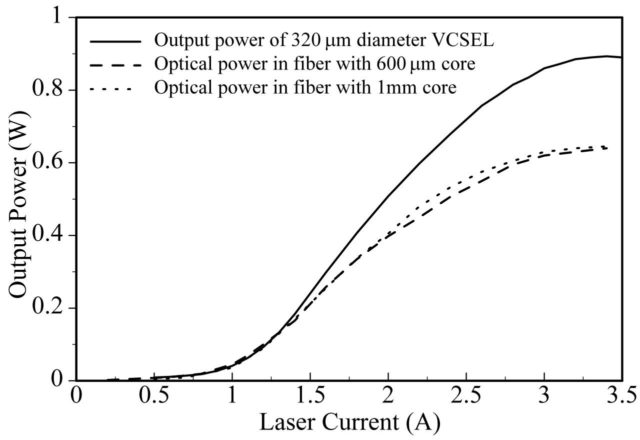

Fig. 8. Optical output power of the laser and launched power at the far end of two 10 meter long large-core fibers of different diameters.

ric far-field pattern the beam can easily be focused or collimated using a single simple lens. In comparison to edge-emitting lasers the low divergence beam is astigmatism free and shows no filamentations.

In order to demonstrate the favorable beam characteristics we have coupled light from a 320 μm diameter VCSEL into two large-core 0.6 and 1.0 mm diameter fibers in a simple butt-coupling arrangement. As indicated in Fig. 8, more than 600 mW of fiber coupled power is measured at the far end of the 10 m long fibers of 0.37 numerical aperture, corresponding to more than 70 % coupling efficiency.

5. Conclusion

In conclusion we have fabricated high-power VCSELs with proven potential for applications requiring output power in the Watt regime. Single devices with active diameters of 320 μm show record high output powers of 0.89 W in cw-operation at room temperature and up to 10 W under pulsed condition which is only limited by the current source. The launched optical power in a large-core diameter fiber by simple butt-coupling is more than 600 mW corresponding to a coupling efficiency of more than 70 %.

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