Highly Efficient Single-Mode Oxide Confined GaAs VCSELs

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We have optimized MBE grown GaAs VCSELs emitting at 840 nm wavelength for maximum single-mode output power. Devices of 3.5 μm diameter show record high single-mode cw output power of 4.8 mW and above 80% butt-coupling efficiency into single-mode fiber. Stable single-mode operation with 3 mW optical output power over a temperature from −10 to +70°C has been demonstrated.

1. Introduction

Increasing single-mode output powers is one of the major issues in vertical-cavity surface-emitting laser (VCSEL) research. Fundamental mode oscillation is desirable for all applications requiring free-space propagation like optical reading and writing or two-dimensional interconnects. Also high performance optical links utilizing single-mode optical fibers and taking advantage of the unique coupling efficiencies of VCSELs would largely benefit from the availability of improved devices. The maximum single-mode output power of 4.4 mW was still obtained with a proton-implanted VCSEL showing strong saturation effects in the light-current characteristics [1]. Single-mode operation is more difficult to obtain with the new class of selectively oxidized VCSELs due to the inherent index guiding properties of the oxide aperture [2]. We have recently demonstrated the beneficial effects of reduced index guiding on fundamental mode stability by comparing different positions of the oxide layer in the standing wave pattern [P-6] and have achieved single-mode powers up to 2.25 mW [P-35]. Using the same technique this value has been increased to 3.5 mW [3]. In this paper, by further optimizing our devices, we present fundamental mode powers of 4.8 mW, the highest value ever obtained with a VCSEL, and demonstrate efficient coupling to single-mode fibers.

2. Device structure

The investigated top emitting VCSEL structure was grown by solid source MBE. The one-wavelength thick inner cavity contains three active GaAs-Al_{0.2}Ga_{0.8}As quantum wells (QWs) designed for about 850 nm gain peak wavelength. The p- and n-doped Bragg reflectors are optimized for low voltage drop and optical loss. Details of the layer structure can be found in [P-10]. Lateral current confinement is achieved by selective wet oxidation
of a single 30 nm thick AlAs layer placed in the first quarter wavelength layer above the cavity region. This layer is shifted towards a node of the standing wave pattern to reduce the built-in effective index guiding and the optical losses [P-6]. The p-type TiPtAu ring contact on the top side is evaporated after oxidation to achieve good ohmic contacts as well as light emission through the top Bragg reflector. TiAu conducting tracks and bondpads are deposited on a polyimide insulation layer. Polyimide provides a smooth planar surface, good passivation and improves the high frequency behavior due to the small permittivity. Mechanically polishing the GaAs substrate down to 150 µm and evaporating a GeNiAu broad area contact are final process steps.

![Graph](image1)

**Fig. 1.** Output power, applied voltage, and conversion efficiency versus laser current for an optimized single-mode VCSEL with 3.5 µm active diameter.

![Graph](image2)

**Fig. 2.** Spectra of the VCSEL from Fig. 1 for different driving currents.

### 3. Device characteristics

The attainable single-mode power strongly depends on the diameter of the oxide aperture. In Fig. 1, the output characteristics of the most favorable, about 3.5 µm active diameter VCSEL is displayed. Threshold current and voltage are 0.5 mA and 1.8 V, respectively. Maximum single-mode output power is 4.8 mW with a side mode suppression ratio (SMSR) of about 30 dB, as can be seen from the spectra in Fig. 2. This value is obtained for a driving current of 4.1 mA with a wallplug efficiency of 35%. The maximum conversion efficiency of 42% is observed at 2.0 mA at an output power of 2.2 mW. The differential quantum efficiency amounts to about 95% over a large current range above threshold. Smaller or larger diameter devices deliver reduced total or fundamental mode powers, respectively. The light output was measured using a Newport 1830C optical power meter with a calibrated silicon diode, which was directly illuminated. This equipment was cross-checked using a further detector system. The spectra were measured using a microscope objective to couple the laser emission into a 50 µm core fiber and to feed the light to an Anritsu optical spectrum analyzer.
4. Thermal behavior

Lasers with high wallplug efficiencies show low thermal heating and are therefore well suited for operation over a wide temperature range. Fig. 3 shows the optical output characteristics for cw operation, indicating good homogeneity in a temperature range from $-10$ to $+70^\circ C$.

![Graph 1](image1.png)

Fig. 3. Light output power versus current for a $3.5 \mu m$ single-mode GaAs VCSEL for various temperatures from $-10$ up to $+70^\circ C$.

![Graph 2](image2.png)

Fig. 4. Threshold current and laser current required for $3 \text{ mW}$ single-mode output power in an industrially relevant temperature range from $-10$ up to $+70^\circ C$.

Fig. 4 summarizes threshold current and laser current required for $3 \text{ mW}$ single-mode output power over the whole temperature range. Within this range threshold currents vary between $440$ and $550 \mu A$, while laser currents for $3 \text{ mW}$ optical output power range between $2.5$ and $3.1 \text{ mA}$. These homogeneous characteristics should allow technical applications without any temperature stabilization. The emission spectra for different temperatures at $3 \text{ mW}$ output single-mode operation are depicted in Fig. 5. The spectral shift of the emission wavelength with temperature is evaluated to $0.06 \text{ nm/K}$.

5. Coupling efficiency

Highly efficient coupling from VCSEL to single-mode fiber has been already demonstrated earlier for proton-implanted devices [4]. Here we show in Fig. 6 coupling efficiency of an oxide confined VCSEL into a $5 \mu m$ core diameter single-mode (SM) fiber as a function of the lateral displacement $\Delta x$. Measurement was done for butt-coupling to an uncoated fiber without using an index-matching fluid. A lateral alignment tolerance of $3.7 \mu m$ is obtained from the FWHM of the coupling curve. The peak efficiency of slightly above $80\%$ corresponds to a maximum single-mode power of about $3.9 \text{ mW}$ in the fiber, making the device attractive also for larger distance data transmission.
For increasing lateral displacement $\Delta x$ between VCSEL and fiber we expect a decay in coupling efficiency according to [5]

$$\eta = \eta_{max} \cdot \exp \left( -\frac{2\Delta x^2}{w_f^2 + w_L^2} \right),$$

(3)

where $w_f$ and $w_L$ are the spot radii of the fiber and the VCSEL mode, respectively. Maximum coupling efficiency $\eta_{max}$ is determined by Fresnel reflection, tilt, and wavefront curvature. For the 5$\mu$m core diameter fiber of numerical aperture 0.14, the spot radius is $w_f = 2.5\mu$m at 840 nm wavelength. From the gaussian decay of the coupling efficiency in Fig. 6 we infer a spot radius of $w_L = 1.9\mu$m which seems reasonable for the VCSEL of 3.5$\mu$m oxide aperture diameter used in the experiment.

6. Conclusion

In conclusion, we have improved the single-mode behavior of oxide confined VCSELs emitting at 840 nm wavelength by optimizing the optical confinement. Record high single-mode output power of 4.8 mW is achieved for a 3.5$\mu$m active diameter device when the 30 nm thick oxide aperture is displaced towards the node of the standing wave pattern. Stable cw single-mode operation at 3 mW optical power is found over a temperature range from $-10$ up to $+70^\circ$C. The butt-coupling efficiency into a 5$\mu$m diameter single-mode fiber is 80% resulting in 3.9 mW power in the fiber.
References


