Long-Wavelength VCSELs with Enhanced Modulation Bandwidth

- Invited Paper -

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Abstract
1.55-µm vertical-cavity surface-emitting lasers with superior modulation bandwidth in excess of 10-GHz up to 85°C and reduced parasitics are demonstrated. Output power and threshold are invariant with temperature. Bit-rates of 12.5 or 17-Gb/s are expected.

Introduction
High-Speed vertical-cavity surface-emitting lasers (VCSELs) with internal bandwidths exceeding 20 GHz have been presented recently emitting in the near infrared spectrum [1-2]. As this waveband can only be used for short distances up to some 300 m, there has been vast effort in developing long-wavelength, high-speed VCSELs with steady development [3-7].
Especially long-wavelength VCSELs with buried tunnel junction (BTJ) have shown promising results and record-high modulation bandwidths.
Nowadays, the market demands cost-effective 100G Ethernet solutions. However, optoelectronic devices being able to provide these bandwidths are not available yet. Therefore, higher laser bandwidth is demanded for the projected higher data-rates, favourably provided by a cost-effective device at long wavelengths and high temperatures range up to 85°C for uncooled operation.
In this paper we present our latest high-speed long-wavelength BTJ VCSELs with superior bandwidths up to 85°C.

Low Parasitics Design
The lasers under investigation were grown in by molecular beam epitaxy on InP substrate. The high-speed 1.55 µm VCSEL structure is an improved version of the device as described in [4], with optimized active region, detuning, mirror-reflectivities and doping levels. The schematic layout of the laser chip is shown in Fig. 1. BCB is used as low-dielectric constant passivation eliminating contact pad capacitances. For high laser bandwidth and sufficient gain at elevated temperatures, the active region was composed of 7 heavily strained (2.5% of compressive strain, pseudomorphic) InAlGaAs quantum wells going near borderline of critical layer thickness. For the presented device the threshold current was designed to be lowest at 60°C heat-sink temperature. This was achieved by a large mode-gain offset resulting in negative T_0 values. Due to the BTJ, which allows the elimination of nearly all *p*-conducting material with higher electrical resistances and optical losses, a

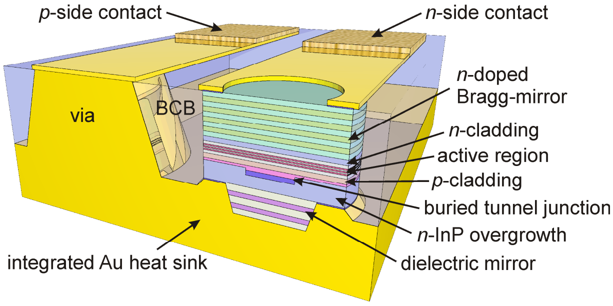

Fig. 1. Schematic cross-section of a high-speed 1.55 µm InP-based BTJ VCSEL. The device is mounted epi-down on a electroplated gold pseudo-substrate. The InP substrate is removed while manufacturing. Both *n*- and *p*-contact can be accessed on top. Contact-pad capacitances are minimized.

differential series resistance as low as 40-50 Ω has been achieved, impedance matched to electrical drivers.
As the parasitic response of our VCSELs can be well modeled by a first-order equivalent circuit [5], a three-pole filter function including relaxation-oscillation frequency f_R, intrinsic damping γ and parasitic roll-off f_p describes the response of our VCSEL well, allowing several intrinsic parameters, to be extracted. Constant terms in Eq. (1) are the differential quantum efficiencies η_d of laser and detector.

$$H(f) = \eta_{d,L}\eta_{d,PD} \cdot \frac{f_R^2}{f_R^2 + j\frac{\gamma}{2\pi} f - f^2} \cdot \frac{1}{1 + j\frac{f}{f_P}} \qquad (1)$$

Even though our devices in reference design [4] showed excellent high-speed behaviour for small chip diameters, the bandwidth of devices with a larger semiconductor chips were still clearly limited by device parasitics. By reducing the doping levels of the blocking diode next to the BTJ from 5 to $1 \cdot 10^{17}$cm^{-3}, the parasitic capacitance was significantly lowered, boosting the modulation bandwidth from below 7 GHz to 9 GHz.

Modulation Performance
VCSELs are characterized by very high carrier and photon densities in the optical resonator causing a damped modulation response. Consequently, low parasitics are especially important for VCSELs as the smaller relaxation oscillation overshoot cannot compensate a parasitic roll-off. In Fig. 2, a superior modulation performance can be identified over a wide temperature range. The 3-dB bandwidth exceeds 12 GHz at 25°C, is

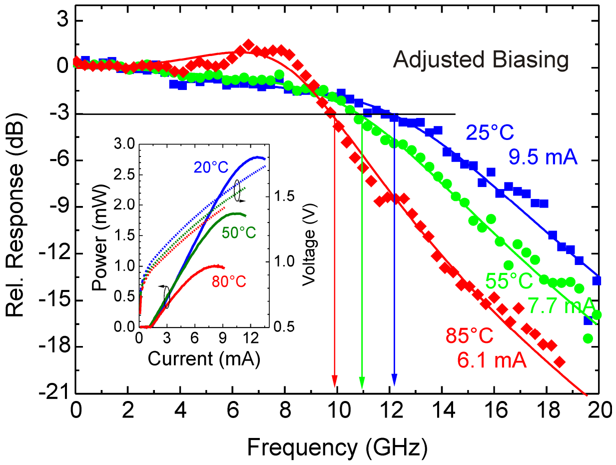

Fig. 2. Small-signal modulation performance of 1.55 µm VCSEL with improved modulation bandwidth and temperature range. At 25°C modulation bandwidth in excess of 12 GHz can be stated and even at elevated temperatures of 85°C 10 GHz modulation bandwidth is available. Scatters: measured data; solid lines: fit to Eq.1. *LIV*-characteristics given as inset.

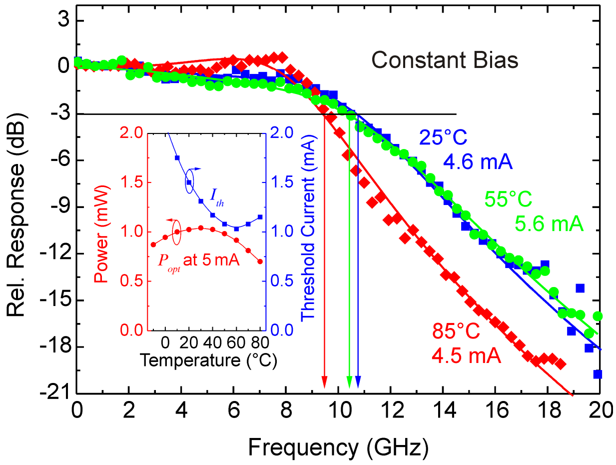

Fig. 3. Temperature behaviour of VCSEL output-power, threshold current and modulation bandwidth. For a given bias current as low as some 5 mA, bandwidths of 10 GHz are achieved invariant to temperature change. Furthermore, the output power remains practically constant around 1 mW redundantising monitor diodes.

11 GHz at 55°C and 10 GHz at 85°C. The *LIV*-performance is given as an inset stating more than 2.5 mW at room temperature and 1 mW at 80°C. A detailed investigation of intrinsic laser parameters could clearly demonstrate a lowered *K*-factor from 0.4 to 0.3 ns, yielding an improvement of the damping limit [7].

Uncooled Operation

The VCSELs presented here were especially designed uncooled operation with superior and constant rating rather than peak-performance at a certain fixed temperature.

For classical distributed feed-back lasers, the output-power at a certain bias current is strongly dependent on the heat-sink temperature, requiring a monitoring and closed-loop control of the laser power, raising the cost of the laser package. As demonstrated in Fig. 3, both laser bandwidth and output power are practically constant for a reasonably low driving current of some 5 mA. This unique behaviour is achieved by the good heat-sinking together with the well-tailored mode-gain offset.

Conclusions

In this paper we present our 1.55 µm BTJ-VCSELs with improved high-speed and high-temperature performance. Internal parasitics have been drastically reduced by redesign of doping-levels. Modulation bandwidth at 5 mA is well sufficient for 10-Gb/s over a temperature-range from 0-85°C at practically constant output powers around 1 mW. Internal relaxation oscillation frequencies could also be improved by higher differential material gain from highly strained quantum-wells. At room temperature we present a record-high modulation bandwidth above 12 GHz enabling potential data-rates of 17 Gb/s for 100G Ethernet.

Acknowledgements

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