PhoxTroT

Photonics for High-Performance, Low-Cost & Low-Energy Data Centers, High Performance Computing Systems: Terabit/s Optical Interconnect Technologies for On-Board, Board-to-Board, Rack-to-Rack Data Links

Collaborative Project
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Report on 1.55 µm BTJ-VCSEL with > 25 Gb/s modulation speed at room-temperature

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Abstract:
This Deliverable reports the development of InP-based vertical-cavity surface-emitting lasers with buried tunnel junction (BTJ-VCSEL). The emission wavelength is around 1.55 µm. The task is to demonstrate high-speed, power efficient VCSELs that allow modulation ≥ 25 Gb/s at room temperature. These devices will be used in active optical cables (AOC) or on-board optical interconnects.

Keywords: vertical-cavity surface-emitting laser (VCSEL), modulation, tunnel junction, InP, optical interconnect

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1 Executive Summary

This deliverable is a progress report on the design, fabrication and modulation characteristics of 1.55 µm BTJ-VCSELs. The preliminary target at month18 is 25 Gb/s at room temperature. The theory of high-speed VCSELs is reviewed and it is shown that the intrinsic limitation can be pushed to much higher frequencies by shortening the length of the cavity. Vertilas manufactured such VCSELs and provided samples to partners within PhoxTroT. The modulation performance is demonstrated with S-parameter measurements and open eye diagrams at 25 Gb/s. The path towards making BTJ-VCSELs with 40 Gb/s modulation speed is briefly outlined.

2 Introduction

This deliverable reports the development of vertical-cavity surface-emitting lasers with buried tunnel junction (BTJ-VCSEL). The emission wavelength is 1.55 µm. The task is to make high-speed VCSELs that allow modulation at ≥ 25 Gb/s at room temperature. These devices will be used in active optical cables (AOC) or on-board optical interconnects.

2.1 Document structure

The present deliverable is split into five sections:

- Methodology
- Target specifications for 25 Gb/s VCSELs
- Fabrication of BTJ-VCSELs
- Characterization and results
- Summary

2.2 Audience

This document is internal to PhoxTroT project consortium.

3 Report on 1.55 µm BTJ-VCSEL with > 25 Gb/s modulation speed at room-temperature

3.1 Methodology

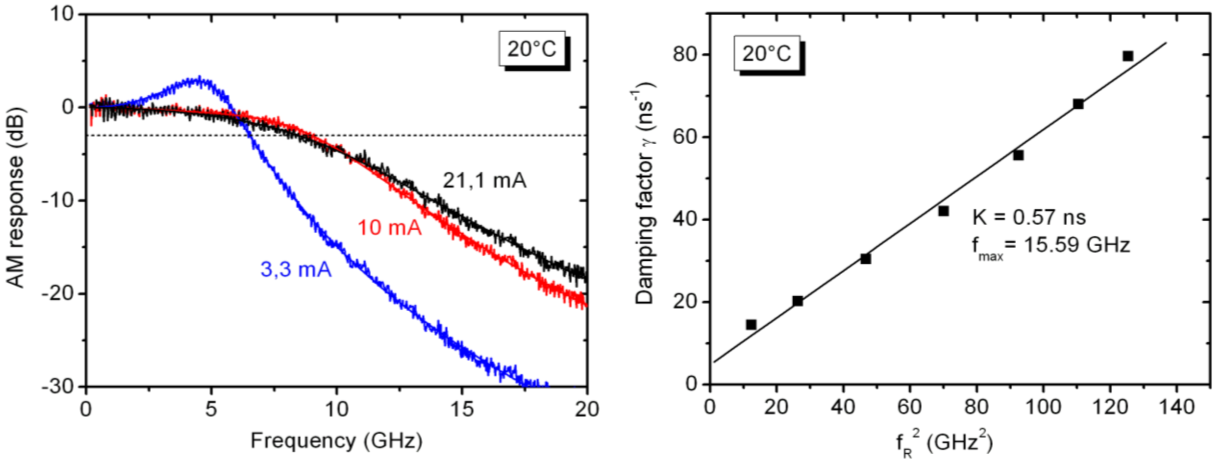
The technology for BTJ-VCSELs is based on InP which is the common and mature material system for optoelectronic devices at telecom wavelengths. The key element of the VCSEL is the buried tunnel junction (BTJ) which allows for substitution of most of the lossy p-type material around the active region with electrically and thermally advantageous n-type layers.

While there already exists a version for modulation at data rates of 10 Gb/s where parasitics are reduced by applying a low-k dielectric material (BCB) around the functional cavity [1], the modulation response suffers from over-damping in the long cavity. The long cavity is composed of an active region between cladding layers and one distributed Bragg reflector (DBR) made from semiconductor materials with low refractive index contrast. Hence, many mirror pairs are needed to build up a sufficient reflectivity and the effective penetration depth into this DBR adds up to the cavity length. The second mirror is a hybrid DBR made from dielectric materials and gold. The materials exhibit a much larger refractive index contrast and thus only a few pairs are needed to build up a high reflectivity.

The modulation response of a laser is described by the three-pole transfer function [2, 3]:

$$H(f) = \frac{A \cdot f_R^2}{f_R^2 - f^2 + j\frac{f}{2\pi}\gamma} \cdot \frac{1}{1 + j\frac{f}{f_P}},$$

with resonance frequency: $f_R = D\sqrt{I - I_{th}}$, damping factor: $\gamma = K \cdot f_R^2 \propto \tau_P$, and parasitic bandwidth: f_P. The *D*-factor describes how the resonance frequency increases with bias current above threshold I_{th}. The *K*-factor is a measure for the maximum, damping-limited modulation bandwidth: $f_{max} = 2\pi\sqrt{2}/K$. The photon lifetime $\tau_P \propto R, L$ is proportional to the mirror reflectivities and the cavity length. Hence, by making the cavity shorter, the photon lifetime and thus the damping can be reduced without compromising the laser threshold. The following Fig. 1 shows examples of the amplitude modulation (AM) response of a long-cavity VCSEL at different bias currents (the measurement setup is described in section 3.4. The maximum 3dB-modulation bandwidth is below 10 GHz. By curve fitting the above transfer function and plotting the resulting damping factors over the squared resonance frequencies one obtains the *K*-factor and a maximum intrinsic modulation bandwidth of



15.6 GHz.

Fig. 1 Measured small-signal AM response of a conventional long-cavity BTJ-VCSEL (left) and resulting parameters from curve fitting (right).

shows a sketch of such a so-called short-cavity BTJ-VCSEL [4].

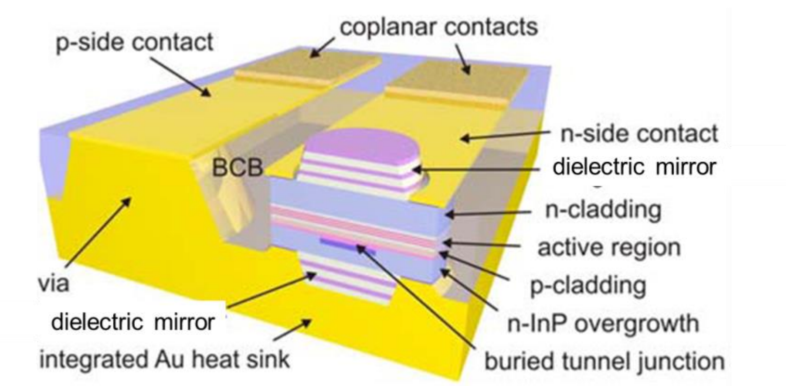


Fig. 2 Schematic cross-section of a short-cavity VCSEL.

3.2 Target specifications for 25 Gb/s VCSELs

The following table summarizes the target specifications for BTJ-VCSEL with ≥ 25 Gb/s modulation speed at room-temperature. The important parameter here is the small signal 3dB bandwidth, which is a measure for the large signal modulation capability. The output power affects the resonance frequency through the *D*-factor and is also important to overcome losses in the optical link. Likewise, a low threshold current increases the resonance frequency and reduces the power consumption of the VCSEL, as it reduces the optimum bias point (current, voltage) for modulation. A narrow divergence angle simplifies the coupling of the laser beam into optical fiber or waveguides. A sidemode suppression ratio of 30 dB or greater is the criteria for a singlemode laser.

Table 1 Target specifications for 1.5µm BTJ-VCSEL with 25 Gbit/s modulation speed.

	Target Specification for 25 Gbit/s					
	Symbol	**Min.**	**Typ**	**Max**	**Unit**	**Conditions/ Comment**
Average Power	P_{av}	2 1	3 1.5	5 2.5	mW	T_o=20°C T_o=80°C
3dB Bandwidth	S_{21}	14	18		GHz	T_o=20°C
Slope efficiency	η	0.2	0.3		mW/mA	T_o=20°C
Differential resistance	R_{diff}	30	35	70	Ω	
Threshold Current	I_{th}	0.5 1	1.5 2	4 4	mA	T_o=20°C T_o=80°C
Operating Current	I_o		15	30	mA	
Operating Voltage	V_{max}		1.6	2.2	V	P_{max}, T_o=20°C
Beam divergence	FWHM	8	12	15	deg	
Side Mode Suppression Ratio	SMSR	30	40		dB	
Wavelength	λ	1520	1550	1580	nm	P_{av} T_o=20°C,80°C
Operating Temperature	T_{op}	0	20	80	°C	Temp control

3.3 Fabrication of BTJ-VCSELs

Vertilas fabricated both long- and short-cavity devices based on its proprietary BTJ-VCSEL technology which will not be detailed here. Fig. **3** shows a scanning-electron-microscope (SEM) image of a fabricated short-cavity VCSEL corresponding to the sketch in
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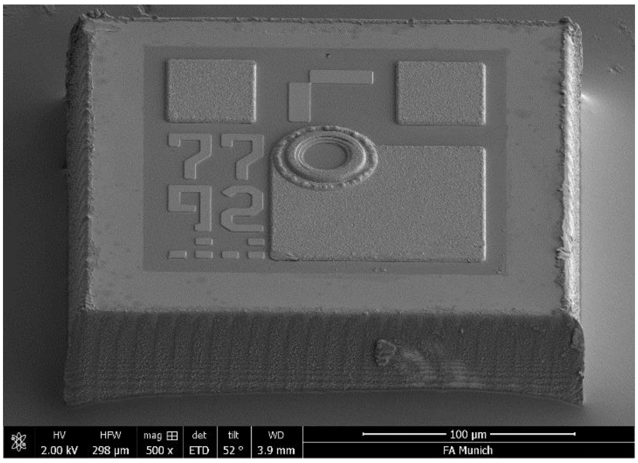


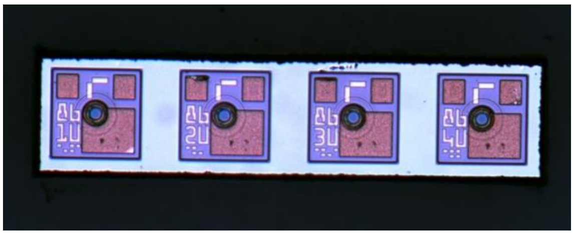


Fig. 3 SEM image of fabricated short-cavity BTJ-VCSEL (left) and microscope image of a 1x4 VCSEL array (right).

3.4 Characterization and results

<u>Static performance</u>

The static performance of the VCSEL is characterized on-wafer before dicing single emitters or arrays. An automated probing station measures the light-current-voltage (LIV) characteristics and the optical spectrum at temperatures between -10 and 90°C. DC-measurements at room temperature of a short-cavity VCSEL with 6 µm BTJ are shown in

Fig. 4. The threshold current is 1.5 mA and the VCSEL emits up to 3.5 mW of optical power. At thermal rollover the VCSEL consumes 16 mA*1.8 V=29 mW. The typical bias point for digital modulation is around half the rollover current, where the power consumption is only 8 mA*1,4 V=11.2 mW. The differential resistance is around 50 Ω. The VCSEL emits in single fundamental mode with a sidemode suppression of 43 dB. The VCSEL emits in the circularly symmetric, fundamental Gaussian mode with a Full Width Half Maximum divergence angle of approximately 13°. The mode field diameter at the beam waist is approx. 6 µm, located around 2 µm beneath the top surface of the short cavity VCSEL.

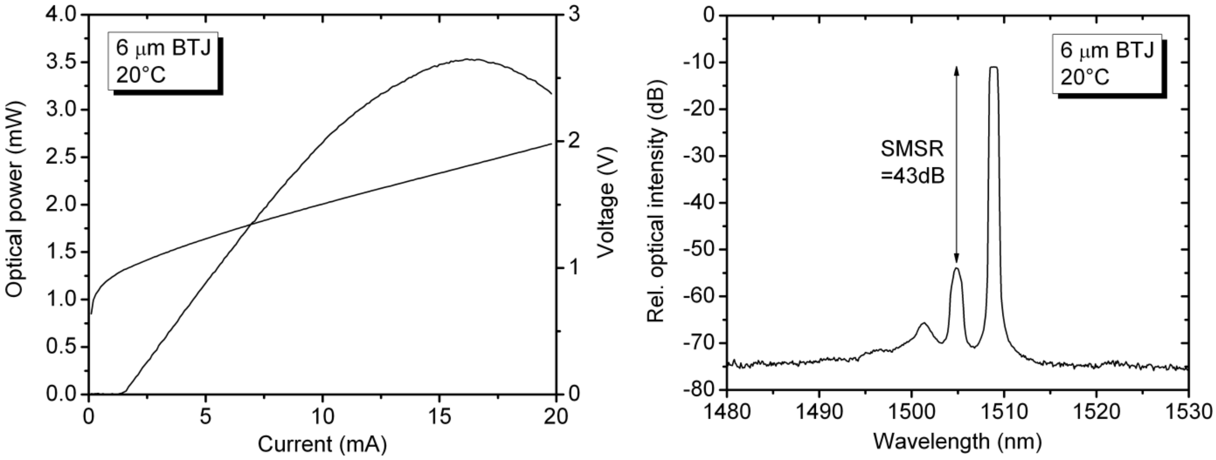


Fig. 4 LIV-characteristic (left) and optical spectrum (right) of a short-cavity VCSEL with 6 µm BTJ.

Dynamic performance

The dynamic performance of the VCSEL is characterized using a network analyzer. The DC bias current is combined with a sinusoidal small signal and fed to the VCSEL through microwave cables and a microwave probe. The stimulated emission from the VCSEL is coupled into a singlemode fiber and converted into an electrical signal via a high-speed photo-receiver. The network analyzer compares the amplitude of the receiver signal at different frequencies. The measured amplitude modulation (AM) response of a long-cavity BTJ-VCSEL is shown in Fig. 1 and the corresponding analysis is discussed in section 3.1.

The small signal analysis of a short-cavity VCSEL with 6 µm BTJ is shown in Fig. **5**. The 3dB modulation bandwidth cannot follow the resonance frequency and reaches a maximum of 14 GHz, while the resonance frequency goes up to 16 GHz. The theoretical limit due to damping is 28.7 GHz and nearly doubled compared to the long-cavity VCSEL in Fig. 1. Obviously, the short-cavity pushes the intrinsic limit and reveals other limitations we have to deal with before we can take full advantage of the high-speed VCSEL.

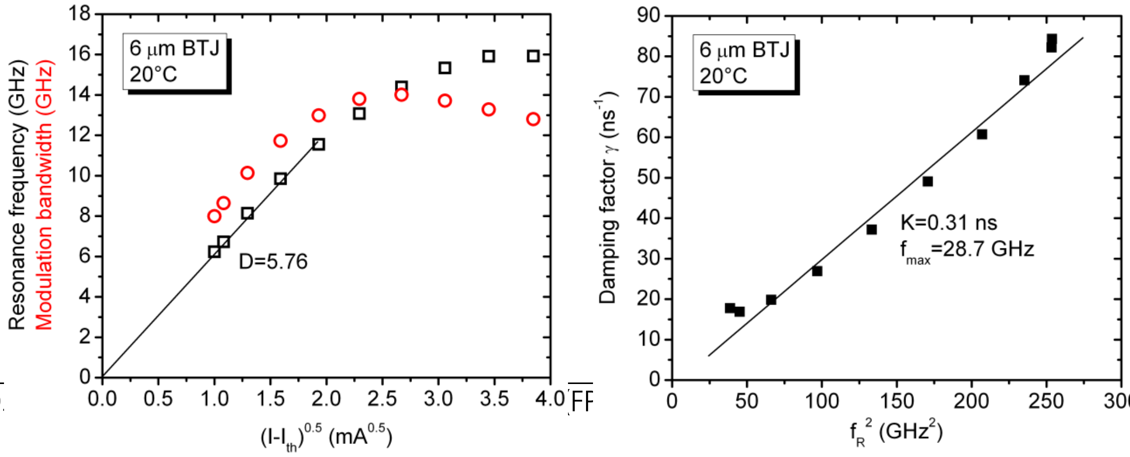
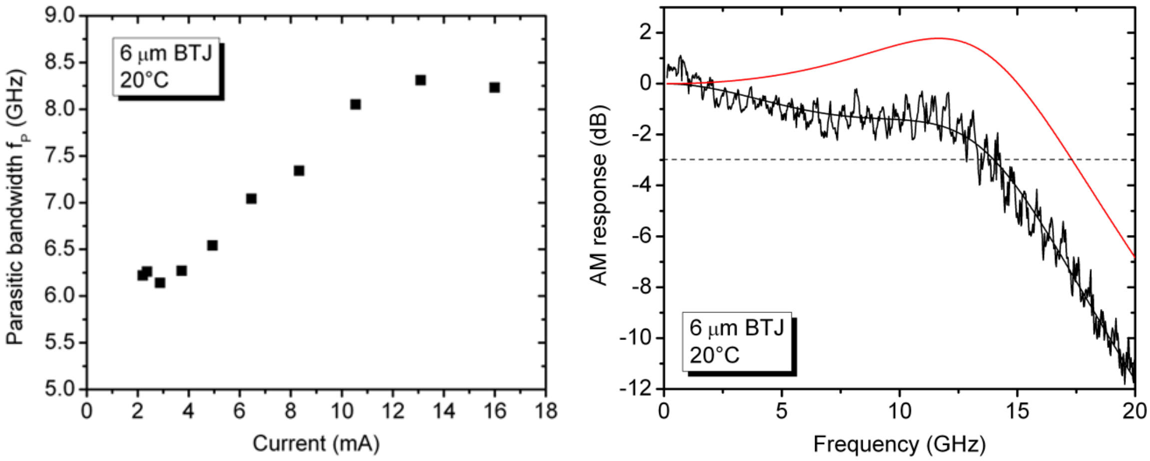


Fig. 5 Small signal analysis of a short-cavity VCSEL with 6 µm BTJ: resonance frequency and 3dB modulation bandwidth (left), damping factor (right).

Fig. **6** (left) shows the extracted parasitic bandwidth at different bias currents. At 8.3 mA, where the 3dB modulation bandwidth reaches its maximum, the parasitic bandwidth is only around 7.5 GHz. Clearly this parameter needs improvement in order to improve the overall modulation response. Fig. **6** (right) shows the measured AM response at 8.3 mA and the corresponding curve fit (in black). The red curve is simulated modulation response assuming parasitic bandwidth of 15 GHz, while keeping the other parameters (f_R, γ) at the



fit values. With reduced parasitics, the 3dB modulation bandwidth is extended to 18 GHz.

Fig. 6 Small signal analysis of a short-cavity VCSEL with 6 µm BTJ: parasitic bandwidth (left) and AM response at 8.3 mA (right) with curve fit (black) and simulation assuming a doubled parasitic bandwidth of 15 GHz (red).

As one measure, the parasitic bandwidth will be improved with smaller contact pads, as shown in Fig. **7**. Another approach is shrinking the mesa diameter and thus reducing the junction capacitance.

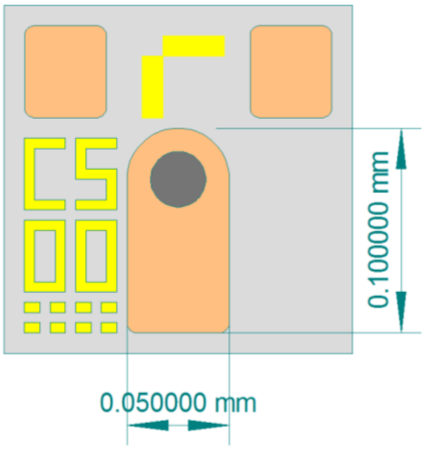


Fig. 7 New layout for reducing the parasitic pad capacitance.

The 3dB-modulation bandwidth, where the small signal amplitude is reduced to 1/2 of its low frequency value, indicates the large signal modulation capability.
For digital modulation, the DC bias is superimposed with a non-return-to-zero pseudorandom bit sequence of length 2^7-1 at a data rate of 25 Gb/s and the optical eye

diagram in Fig. **8** is recorded with a high-speed photo receiver and a sampling oscilloscope. As for typical applications, the modulation has an extinction ratio of at least 5 dB and the optical eye fits the 100 Gigabit Ethernet mask (100GBASE-LR4) with an 8% mask margin. For the presented optical eye, a DC current of 13 mA and a peak to peak modulation voltage of 766 mV are used.

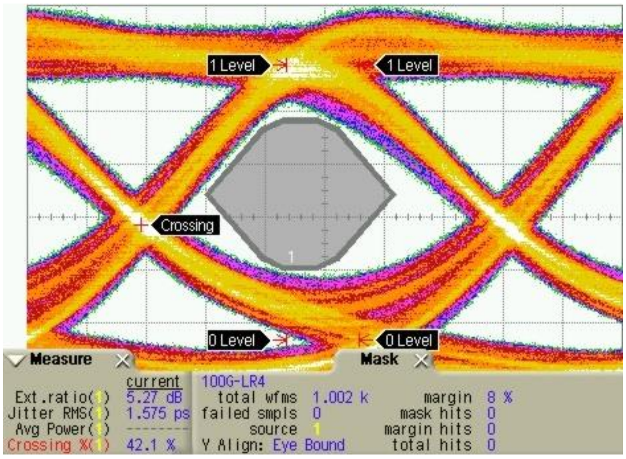


Fig. 8 Optical eye diagram of short cavity-VCSEL at 25 Gbs/s data rate at 20°C.

4 Summary

The theory for modulation of VCSELs is presented and it is shown that the modulation speed can be enhanced by reducing the cavity length. Short-cavity VCSELs with 1310 nm and 1550 nm wavelength have been developed, manufactured and characterized. The optical output power goes up to 3.5 mW and the small signal modulation bandwidth reaches 14 GHz at room temperature. Analysis further shows that the modulation bandwidth is still limited by the parasitic capacitance, which will be further reduced in the next generation VCSELs within PhoxTroT. Clear and open eye diagrams at 25 Gb/s (100 Gigabit Ethernet) with 5 dB extinction ratio were successfully demonstrated. To achieve even higher bit rates or operating temperatures, modulation experiments in next generation VCSELs will be combined with optimized drivers including pulse shaping as reported by imec in D4.2.

5 Appendix

5.1 References

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