PROJECT FINAL REPORT

Grant Agreement number: 224259

Project acronym: SUBTUNE

Project title:Widely Tuneable VCSEL using Sub Wavelength Gratings

Public Report

Funding Scheme: Collaborative Project

Period covered: from 1st April 2011 to 31st December 2011

Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:

Prof. Dr.-Ing. Peter Meissner

Tel: + 49 6151 162462

Fax: + 49 6151 164343

E-mail: p.meissner@ieee.org

Project website address: www.subtune.org

---

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

Contents

1 Executive Summary

The main tasks of the EU project SUBTUNE were:

- The development of tuneable vertical cavity surface emitting lasers (VCSEL) with large tuning range, high output power and a high suppression of lateral and longitudinal sidemodes
- The tuning is performed by micromechanical actuation using a two chip concept. Using this technology the lower part of the VCSEL (active semiconductor) and the upper part (tuneable membrane) are optimized independently and both parts are adjusted manually to each other. To avoid this additional mounting a new technology using surface micromachining had to be developed to allow on wafer fabrication of many VCSELs simultaneously.
- Stable polarization behavior has to be achieved even during tuning
- The center wavelength envisaged depend on the applications
  - 1.5 μm for application in communication systems and fiber Bragg grating systems
  - 2.0 μm for applications in gas sensing systems
  - 0.8 μm for applications in reconfigurable interconnects
- Prototypes of the developed VCSELs have to be tested in the applications mentioned above.

During the 45 months of intense research we developed prototypes of VCSELs with outstanding properties:

- For a non tuneable VCSEL we achieved world record single mode output power of 6.7 mW and a 3 dB modulation bandwidth larger than 10 GHz. Even at 80°C an output power of more than 2 mW was achieved.
- Using the same active part and combining it with a tunable membrane we achieved a continuous tuning range of 56 nm and modulation bandwidth allowing 10 Gbit/s OOK transmission
- We succeeded in the development of surface micromachining as well for the InP based technology (1.55 μm and 2 μm VCSELs) as for the GaAs based technology (0.8 μm VCSELs).
  - The developed InP based 1.5μm VCSEL showed a world record continuous tuning range of 102 nm with an output power in the range of 2-3.5 mW.
  - We succeeded to develop a tunable VCSEL with an continuous tuning range from 1920 nm up to 1970 nm with an output power in the range of 0.4-1.0 mW.
- Using the GaAs based material system we achieved a tunable VCSEL showing a tuning range of 24 nm and which could be directly modulated at 5 Gb/s.
- Sub wavelength gratings were implemented as well in GaAs as in InP based tunable VCSELs. For both types of VCSELs we achieved polarization stable operation over the tuning and current range.

Though the prototype devices showed an excellent performance the implementation of the VCSEL in an application system is a real challenge. Here further optimization in terms of reliable packaging is a must for real system applications. But even though we could perform first very promising experiments in communications showing an error free 5 Gbit/ back to back transmission with the surface micromachined VCSEL at a wavelength of 870 nm. At 1550 nm we achieved a 50 km single mode fiber transmission with an external modulator showing the same performance as an external cavity laser. In gas sensing and fiber Bragg sensing first preliminary experiments were performed. Since the performance of the non packaged devices are very promising the partners of the project plan to continue these experiments using VCSELs being already in the processing stage.

2 Summary description

Wavelength tunable lasers with selectively wavelength-addressable spectrum are among the key components to build future reconfigurable optical networks and they are in demand as spare modules in a cost effective and compact wavelength division multiplex infrastructure. Moreover, a broadband and continuously tunable laser with a high purity emission spectrum is a versatile tool for many sensing applications. For example, the emission of greenhouse gases can be controlled by laser absorption spectroscopy using widely tunable lasers resulting in a very high sensitivity. An important feature of these lasers is their ability to monitor several species of gases simultaneously. A fiber Bragg grating (FBG) transducer is a well established optical fiber sensing technology to perform temperature, strain and pressure measurements. Today the most popular mean to interrogate a FBG transducer is based on a broad band illumination. Replacing this light source by a widely tunable laser will result in a much better signal to noise ratio, compactness of the system and a low overall price. The vertical-cavity surface-emitting laser (VCSEL) is the ideal candidate due to its inherent longitudinal single-mode behavior, low power consumption and compactness.

The project SUBTUNE (Widely tunable VCSELs using sub wavelength gratings) is a STREP (Specific Targeted Research Project) sponsored by the European Commission which deals with the development of continuously tunable lasers and their application in communication and sensing systems. SUBTUNE started on the 1st of April, 2008 and involves eight partners from six countries. Within this project a novel concept for widely and continuously wavelength-tunable single-mode laser diodes in the 750-2100 nm wavelength range was developed. The underlying VCSEL structure is thereby completed by a micro-machined moveable Bragg-mirror (see figure 1). Both electro-thermal and electrostatic actuation schemes were developed by the consortium.

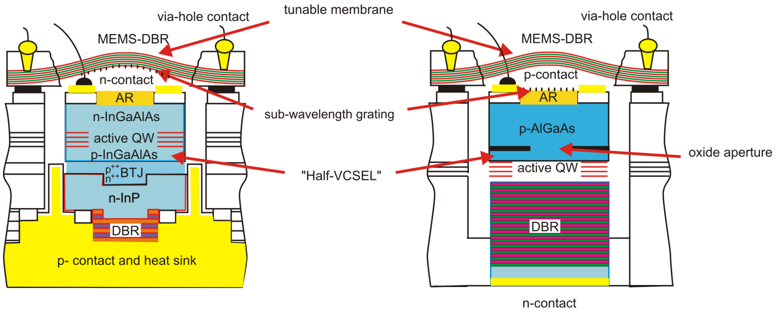


Figure 1: Structure of a tunable long-wavelength VCSEL with sub wavelength grating for the long (left hand side) and short wavelength (right hand side) region.

The Technische Universität Darmstadt coordinates the project, fabricates the tunable micromachined membranes and integrates the membranes with the active parts. Two partners are developing the semiconductor active parts of the VCSELs, Chalmers University of Technology (Sweden) is engaged in the design and fabrication of GaAs-based active parts for the wavelength range between 750 nm and 1000 nm, while the Technische Universität München (Germany) is mainly doing the design, fabrication and optimization of InP-based active parts for the wavelength region between 1.3 μm and 2.1 μm. Tyndall National Institute at the University of Cork (Ireland) characterizes the devices and assesses their particular suitability for telecommunication applications. The Consiglio Nazionale della Ricerche (Italy) develops the computer code for the design and optimization of the tunable lasers with curved micromachined membranes and sub wavelength gratings. The company LEISTER (Switzerland) acts as an end user of the tunable devices and develops a gas sensing system using the laser for simultaneously monitoring two species with one laser. The Commissariat l'Energie Atomique (France) develops a fiber Bragg grating sensing system utilizing the tunable lasers. The company VERTILAS (Germany) concentrates on sophisticated qualification procedures (burn in and ageing) as well as packaging issues.

The idea of the new device is an optimized optical cavity design to achieve maximum support for the fundamental mode. This was realized by matching the curvature of the micro-mirror to the phase of the fundamental mode while suppressing the undesired polarization mode by means of a sub-wavelength grating. This technology is capable of selecting the single fundamental mode from relatively large apertures. The resulting output power is high and very good side-mode suppression was achieved even during tuning. The project developed both, long wavelength InP-based VCSELs ranging from 1.3 μm to 2.1 μm and short wavelength using the GaAs material system with wavelength down to 750 nm, thus introducing tunable VCSELs in a broad range of the optical spectrum.

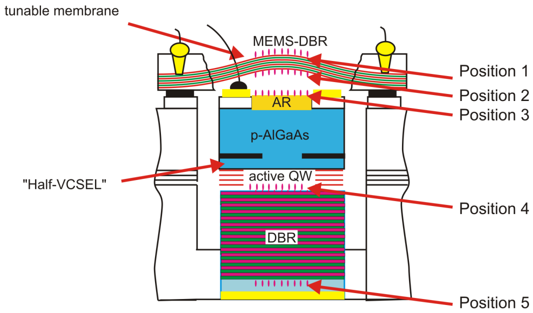
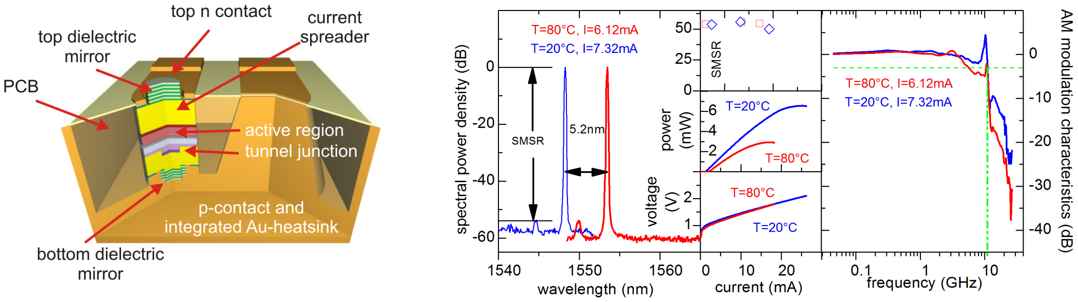


Figure 2: Possible positions of the SWGs in our micromechanically tunable VCSELs

Essential for an optimal design of the tunable VCSELs is the accurate modeling of the device. The main difference and challenge compared with standard non tunable VCSELs is the air semiconductor surface inside the cavity, the curved mirror and the sub wavelength grating. The placement of the sub-wavelength-grating is a tradeoff between gain contrast and technological boundaries. Therefore - besides optimization - the main emphasis of the modeling activities was the investigation of the optimum placement of the sub-wavelength-grating (see Figure 2).

The position 5, at the very bottom, shows the largest gain contrast, but also position 2 and 3 are quite promising. In both technologies the optimum positions was not achievable due to technological boundaries, therefore the position 3 was chosen for the GaAs based VCSELs and position 2 for the long wavelength VCSELs.

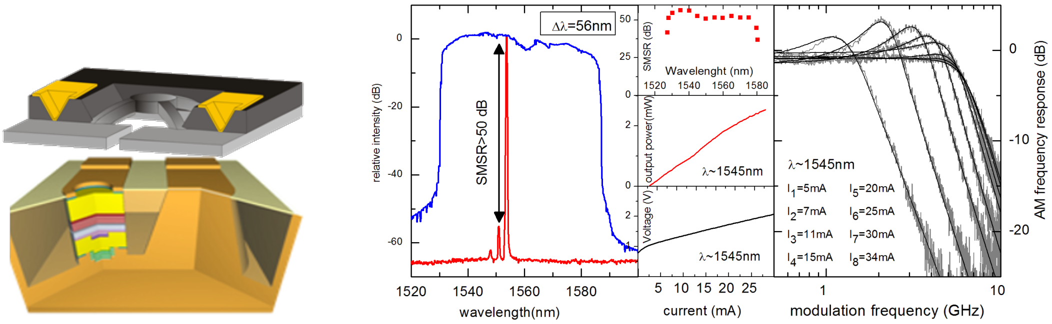


(a) Schematic cross-section

(b) Spectrum, side mode suppression, power current, voltage current and AM modulation characteristics

Figure 3: High-speed non-tunable 1.55 μm InP-based BTJ VCSEL

SUBTUNE succeeded to develop GaAs based VCSELs as well as InP based tunable VCSELs with



(a) Schematic cross-section (b) Spectrum, side mode suppression, power current, voltage current and AM modulation characteristics

Figure 4: High-speed tunable 1.55 μm InP-based BTJ VCSEL

excellent and even world record properties. The "Half-VCSEL" developed by the SUBTUNE project for high speed applications shows a very low resistance since most of the p doped material was exchanged by high conducting n-material due to its buried tunnel junction. Additionally most of the semiconductor material was replaced by low-k material BCB (Benzocyclobutene) resulting in an essential reduction of the capacitance of the device (see figure 3(a)). To investigate the high frequency properties of this design a dielectric mirror is deposited directly on top of this "Half-VCSEL". The resulting non tunable VCSEL showed a world record performance showing an output power of 6.7 mW and a 3 dB modulation bandwidth of 11.2 GHz (figure 3(b)). This device is suitable for high speed communication systems.

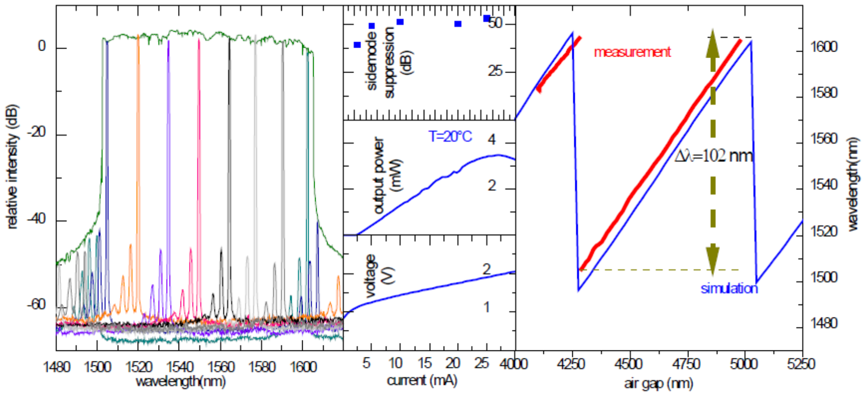


Figure 5: Tuning and power characteristics of a 1.5 μm surface micromachined tunable VCSEL

Using the same VCSEL structure and replacing the top dielectric mirror by a bulk tunable micromachined membrane we succeeded to achieve a tuning range of 56 nm and direct modulation capacity suitable for 10GBit/s transmission systems (see Figure 4). This is a very promising device for flexible high speed communication systems allowing for example the use of the frequency self routing principle.

The bulk micromachining technology has the advantage of being very flexible for the investigation of prototypes with different kinds of mirrors and active "Half-VCSELs", additionally it allows the independent technological optimization of the active laser part and the micromachining of the tunable membrane. The tuning is achieved by sending a current through the beams of the membrane resulting in a thermal expansion and thus an extension of the cavity length and a shift of the wavelength to longer values.

The disadvantage of this technology lies in a very time consuming manual mounting and alignment procedure. Therefore we developed a surface micromachining technology which allows on wafer fabrication of many tunable VCSELs at the same time with lithographic accuracy. Using this surface micromachining technology we succeeded to develop a tunable VCSEL with world record performance showing a tuning range of more of 100 nm (see figure 5). Additionally we see a very good agreement between simulation and measurement. From the simulation we can confirm that the tuning range is determined by the free spectral range.

The widely tuneable VCSEL with the integrated mirror was externally modulated in data transmission experiments and error free transmission over 50 km in single mode optical fibre at 10 Gb/s over a 30 nm tuning range was demonstrated. A penalty of 0.2 dB was measured when compared with a tuneable external cavity laser which was due to residual membrane movement in the non packaged VCSEL. The lasers show great promise for telecommunications applications.

In the table 1 we compare the achievements of the SUBTUNE project with its specifications.

VCSEL Specifications	Minimum Performance	Ultimate Goal	Achieved results					
			InP based			GaAs based		
Centre wavelength [μm]	0.75-2.1	0.75-2.1	1.55		2.0	0.8		
							TUD	Chalmers
			Bulk	Surface	Surface	Bulk	Surface	
Optical output power CW at RT [dBm]	-3	5	4.3	5.5	2	-7	-4.5	-4.5
Transverse sidemode suppression [dB]	30	50	60	45	50	30	30	35
Linewidth [MHz]	50	10	22	90	X	X	X	X
Polarization mode suppression [dB]	30	50	X	X	X	30*	X	X
Tuning range [nm]	30	60	56	102	50	37	13	24
Tuning speed [μs] (full scale wavelength switching) thermal tuning electrostatic tuning	1000	10	1300	1300 5	1100	700Hz	X	100 Hz
Tuning current [mA] Tuning voltage [V]	20...50	10	20...40	20...40 100...200	20...40	10...20	10...26	<16
Bitrate [Gitb/s] Modulation frequency [GHz]	0.56	10	 6	X	X	5 3.2	 3.2	5 6

Table 1: Specification for the tunable VCSEL and achieved results

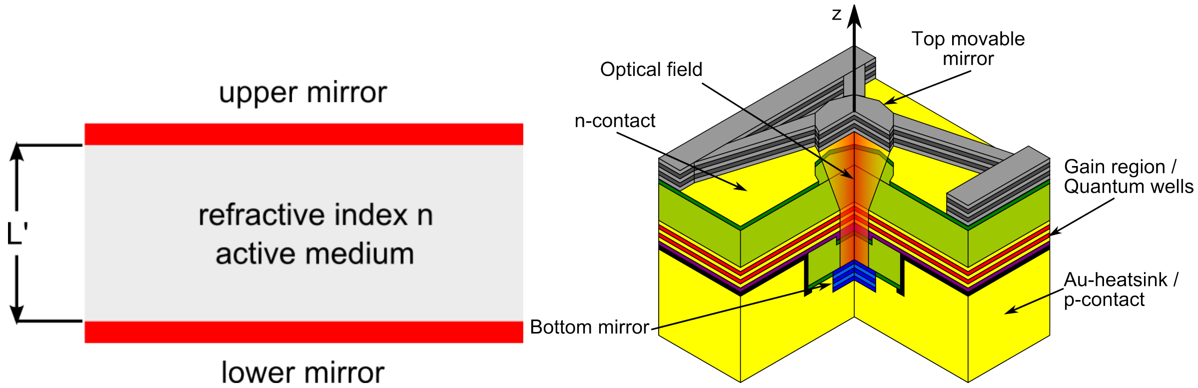
3 Main S&T results

3.1 Introduction

Tunable semiconductor lasers operating in the wavelength region around 800 nm and 1550 nm are an attractive tool for many applications, such as fiber Bragg-grating sensors [21], absorption spectroscopy [2, 18, 17], optical coherence spectroscopy [15] or optical communications [3]. Due to their short cavities Micro-Electro-Mechanical System (MEMS) tunable Vertical-Cavity Surface-Emitting lasers (VCSELs) show inherently longitudinal single-mode behavior enabling continuous broadband wavelength tunability. VCSELs display low power consumption, low threshold current and small beam divergence, the latter significantly simplifies the fiber coupling. The SUBTUNE project was aiming for the development of micro-mechanically tunable VCSEL in the short (c. 850 nm) and long (1550 nm & 2000 nm) wavelength range and to test the developed devices in relevant application fields.

3.2 Over all structure of our tunable VCSELs

The basic physics of a VCSEL can be best explained with the principle of Fabry-Pérot lasers. Such a laser consists of two parallel mirrors with an active gain material for light amplification in between. This can be an electrically pumped semiconductor whose parallel crystal surfaces form a resonator consisting of two plain mirrors. After each reflection, the light passes the electrically pumped gain medium and is amplified.



(a) Simple Fabry Perot resonator (b) Micro-mechanically tunable VCSEL

Figure 6: Comparison of simple Fabry-Perot resonator and micro-mechanically tunable VCSEL

A stable laser mode is only possible if the circulating field between both mirrors reproduces itself in phase and amplitude resulting in a standing wave:

$$L_o = nL' = m\frac{\lambda_m}{2} \Rightarrow \lambda_m = \frac{2nL'}{m} \tag{1}$$

where L_o is the so called optical length, L' is the geometrical cavity length, n the effective refraction index, m an integer and λ_m the emitted wavelengths. The main mechanism for tuning a laser is to change the effective optical cavity length L_o and thus the wavelength λ_m. There exist three parameters for changing the emitted wavelength. The first one is the temperature of the device (thermo optical effect). An increase of the temperature T leads to a change of the refractive index n(T) and thus to an increase of the wavelength. The wavelength change over temperature is typically 0.09 to 0.12 $nm/^oC$ and limited to a continuous tuning range of about 7 nm for standard VCSELs. The second one is the injection current, which changes the carrier density n_c inside the active region and thus the refractive index. The third one is to change the cavity length mechanically. Additionally we can learn from equation 1 that the tuning efficiency becomes much larger if we choose a cavity length as short as possible, e.g.the integer m in equation 1 should be as small as possible. Using this concept of a micro-electro-mechanical (MEMS) tunable VCSEL (see Fig. 6) we achieved a record tuning range of 102 nm[11].

A MEMS tunable VCSEL mainly consists of an electrically pumped active region embedded between two distributed Bragg reflectors (DBR)(see Fig. 6). They are based on the principle of interference and result in very high reflectivities ($> 99\,\%$). These reflectivities are needed since the active region is very thin compared to edge emitting diode lasers and therefore provides only a small round trip gain. One can separate the tunable VCSEL into two main parts. The first part includes the bottom mirror and the active gain region. This part is called "Half-VCSEL", because the second mirror is missing. The second part consists of a curved movable mirror membrane which is suspended on four flexible beams as top mirror [14]. An implemented conductive layer allows thermal heating of the membrane and thus an expansion of the suspension beams. This leads to an increase of the air gap length (see fig. 6). The curved top mirror and the flat bottom mirror of the "Half-VCSEL" are forming a plane-concave Fabry-Pérot cavity. This type of cavity is much less sensitive to tilt angles between the two mirrors compared to cavities consisting of two plane mirrors [20] thus allowing higher tolerances in the fabrication procedures. Furthermore we will see that this approach can be used to further increase the side mode suppression ratio (SMSR) and to guarantee also stable optical properties over the whole tuning range.

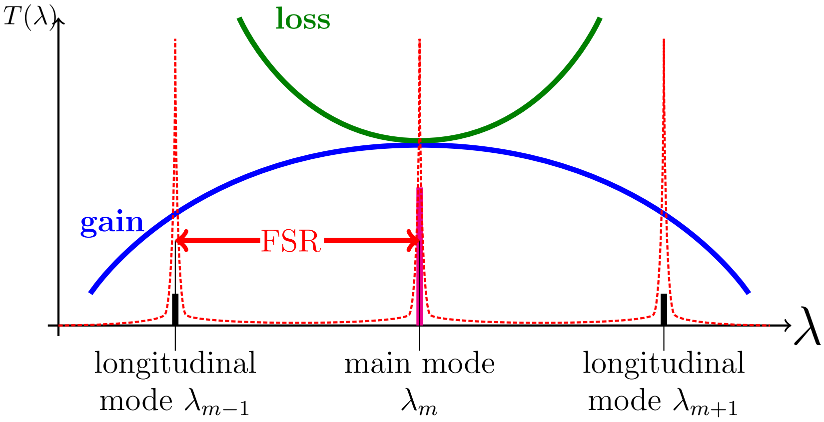


Figure 7: The selectivity of the Fabry-Pérot resonator of a short cavity VCSEL allows only one logitudinal mode (λ_m) to lase. The adjacent longitudinal modes (λ_{m+1},λ_{m-1}) underlie too high losses.

The MEMS tunable VCSELs devices presented can be described as optical oscillators with resonant wavelengths defined by equation (1). The standing waves are the longitudinal eigenmodes of the optical resonator. The free spectral range (FSR) between two longitudinal modes is depicted in figure 7 and given by

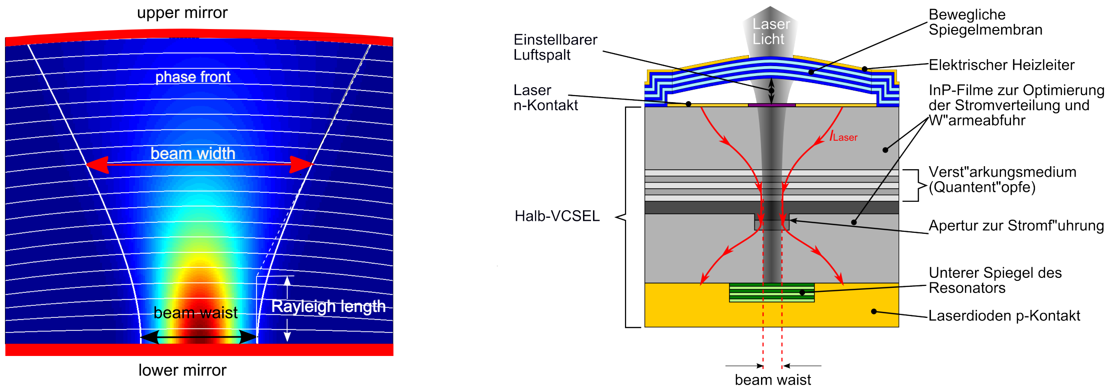
$$FSR_\lambda = \lambda_m - \lambda_{m+1} \approx \frac{\lambda^2}{2L}. \tag{2}$$

This equation illustrates one advantage of VCSELs as tunable laser sources. In comparison to edge emitting lasers, the resonator length of typically $L = 10\,\lambda$ is quite short and leads to a $FSR_\lambda \approx \lambda/20 \approx 80\,\text{nm}$ at a wavelength of $\lambda = 1550\,\text{nm}$. Because of the limited amplification bandwidth of the gain medium $g(\lambda)$, the wavelength dependence of the losses $\alpha(\lambda)$ of the passive resonator and the large spectral distance of the longitudinal modes (Transmission T of the resonator, see figure 7) only one longitudinal mode has a sufficient amplification for lasing (a schematic view of α,g and T is given in figure 7). This intrinsic single mode behavior allows a continuous tuning of the wavelength. Another advantage is the tuning efficiency. A change in the distance of the two resonator mirrors of ΔL leads to a linear shift of the wavelength $\Delta\lambda$ with

$$\Delta\lambda = \Delta L \cdot \frac{2}{m} \tag{3}$$

whereas m is the order of the longitudinal mode. In our example with a typical resonator length of $L = 10\,\lambda$ we get $m = 20$ and therewith $\Delta\lambda = 0.1 * \Delta L$. Whereas a typical edge emitter with $L = 450\,\lambda$ has a tuning efficiency of only $\Delta\lambda/\Delta L \approx 0.005$ which is twenty times smaller. The consequence is, that a reduction of the resonator length effects an increase of the tuning efficiency. Nevertheless a tuning over the whole FSR requires a change of the resonator length of $\Delta L = \lambda/2 \approx 780\,\text{nm}$, which is independent of the resonator length. In conclusion we see that the maximum tuning range of a single mode VCSEL is always smaller than the FSR.

3.3 Resonator geometry and Gaussian modes



(a) Micro-mechanically tunable VCSEL

(b) Micro-mechanically tunable VCSEL

Figure 8: (a) Simple Gaussian beam in a plane concave resonator; (b) Crossection of the tunable VCSEL.

In section 3.2 we introduced a one dimensional model for Fabry-Pérot resonators with indefinitely large plane mirrors and calculated its modes. Since there is no significant index guiding inside our VCSEL the propagation of the optical field can be approximated by Gaussian beams. We wanted to achieve as well longitudinal as transversal single mode behavior and we therefore designed our cavity as a stable plane concave resonator [22]. The three dimensional electrical field distribution of the longitudinal modes inside the resonator can be approximated by the radial symmetric Gaussian beam equation (in cylindric coordinates)

$$E(r,z) = E_0 \frac{w_0}{w(z)} \cdot \exp\left(-\frac{r^2}{w(z)^2}\right). \tag{4}$$

This equation is completely defined with the beam waist $w_0 = w(z = 0)$ of the Gaussian beam and the Rayleigh length $z_0 = \pi w_0^2/\lambda$. The Gaussian beam diverges in z-direction at which $w(z)$ defines the beam radius along the propagation axis z. The phase-front $R(z)$ of the Gaussian beam transforms from a plane wave at $z = 0$ into a spherical wave for $z \to \infty$ with

$$w(z) = w_0\sqrt{1 + \left(\frac{z}{z_0}\right)^2} \quad ; \quad R(z) = z\left(1 + \left(\frac{z_0}{z}\right)^2\right) \tag{5}$$

Thus the Gaussian mode is completely defined by the radius of curvature (RoC) of the top movable mirror membrane and the cavity length L (in z-direction, see Fig. 8), so that the phase-fronts of the Gaussian mode coincide with the mirror geometries. This circumstance causes a plane phase-front at the bottom mirror of the VCSEL with a given beam waist of

$$w_0 = \sqrt{\frac{\lambda}{\pi}\sqrt{L(RoC - L)}}. \tag{6}$$

In this formula the additional reflection at the air "Half-VCSEL" surface is neglected.

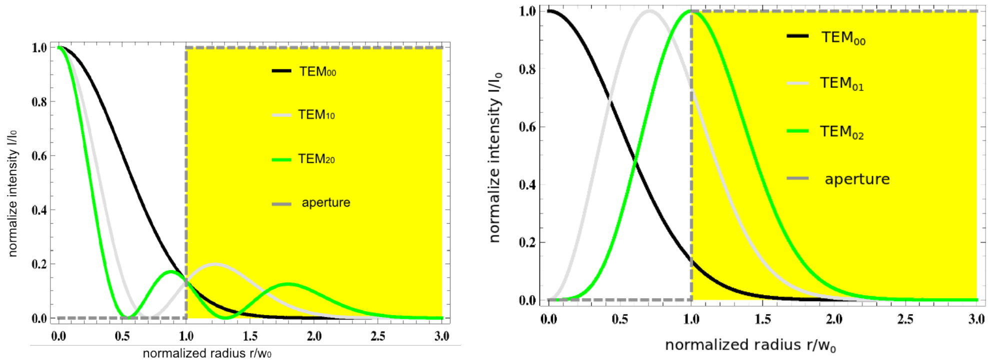
In figure 8(a) a typical Gaussian beam is depicted with its beam waist and its phase fronts. In fact, a rotation symmetric resonator is not restricted to the longitudinal Gaussian modes. Transversal higher order modes fulfill the boundary conditions of the resonator as well. These modes can be described as TEM$_{pl}$ modes with radial and azimuthal order p and l, respectively. In fact, the intensity distributions inside the complex VCSEL device can not completely be described by TEM$_{pl}$-modes but by hybrid modes with longitudinal field components [8]. The Gaussian beam theory can be used as a good approximation. The intensity profile for the TEM$_{pl}$ modes can be calculated with the Gauss-Laguerre-polynomes $\mathrm{L}_p^l(t)$ (in polar coordinates (r, ϕ)) as follows:

$$I_{pl}(r,\phi) = I_0 \cdot t^l \cdot (L_p^l(t))^2 \cdot \cos^2(l\phi) \cdot e^{-t} \quad \text{with} \quad t = 2r^2/w_0^2. \tag{7}$$

For higher order modes, the intensity distribution spreads in radial direction. A cross section view of the higher order radial (a) as well as azimuthal modes (b) is shown in Fig. 9 (the intensity distributions are symmetric to the intensity-axis). This fact allows us to increase the losses for higher order modes with the implementation of an aperture inside the VCSEL structure (colored area in Fig. 9). Thus a significant increase of the SMSR is possible. In a plane concave resonator each TEM$_{pl}$ mode has its characteristic resonance frequency

$$\nu_{plq} = \frac{c}{2L}\left(q + \frac{2p+l+1}{\pi}\arccos\left(\sqrt{1 - L/RoC}\right)\right) \tag{8}$$

with longitudinal order q. The measurement of the emission spectrum allows to identify the lateral modes and thus the side mode suppression ratio (SMSR) as will be shown in section 3.8.



(a) Radial modes

(b) Azimutal modes

Figure 9: Cross section view of the intensity distribution for radial (a) and azimutal Gauss-Laguerre-modes TEM$_{pl}$ (b). The implementation of an aperture inside the resonator (shaded area) allows to increase the losses for higher order modes which leads to a significant increase of the sidemode suppression ratio (SMSR).

3.4 Lateral and longitudinal confinement factor

The size of the integrated aperture is chosen to be in the range of the beam waist of the fundamental Gauss-mode. As illustrated in figure 9, the fundamental mode is nearly not effected by the aperture, whereas the higher order modes have a larger overlap between the intensity distribution and the aperture. The basic principle behind the aperture is to confine the current flowing through the device to a defined diameter D_A (see Fig. 10). Since the gain profile is directly correlated with the current density, the overlap between the lateral gain $g(r,\phi)$ and the transversal intensity distribution $I_{pl}(r,\phi) \propto |E_{pl}(r,\phi)|^2$ for a certain mode p,l can be described by the lateral confinement factor

$$\Gamma_{xy} = \frac{\int |E_{pl}(r,\phi)|^2 g(r,\phi)\, r\, dr\, d\phi}{\int |E_{pl}(r,\phi)|^2\, r\, dr\, d\phi}. \tag{9}$$

Considering a constant gain profile limited by the integrated aperture, one can calculate that $\Gamma_{xy}(E_{00}) > \Gamma_{xy}(E_{pl})$ for p or $l > 0$. Thus the fundamental Gaussian mode has a higher gain compared to higher order transversal modes leading to an increase of the SMSR. With the longitudinal confinement factor Γ_z which quantizes the overlap between the longitudinal intensity distribution of a given mode and the active gain region

$$\Gamma_z = \frac{\int_{d_{gain}} |E_{pl}(z)|^2\, dz}{\int_L |E_{pl}(z)|^2\, dz}, \tag{10}$$

one can calculate the effective gain $\langle g \rangle = \Gamma g = \Gamma_{xy}\Gamma_z g$ for each resonator mode. The longitudinal confinement factor Γ_z compares the thickness of the active region d_{gain} with the resonator length L. Thus equation 10 can be written as[5]

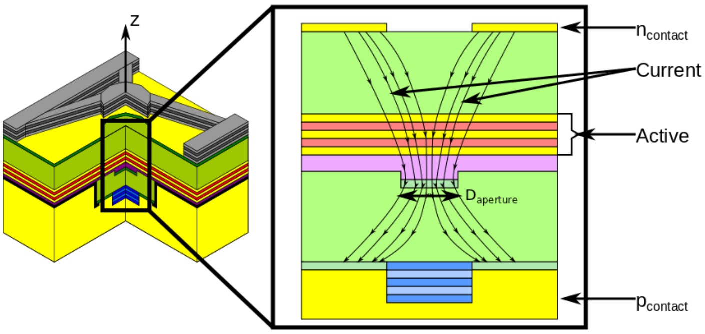


Figure 10: The current flowing from the n- to the p-contact is confined to the diameter D$_{aperture}$ of the integrated aperture. The active region is electrically pumped only within this area which leads to a spatial confinement of the gain.

$$\Gamma_z = \frac{d_{gain}}{L} \cdot \Gamma_r \quad \text{with} \quad \Gamma_r = 1 + \cos(2k_z \Delta z)\frac{\sin(k_z d_{gain})}{k_z d_{gain}}. \tag{11}$$

The relative confinement factor Γ_r describes the overlap between the standing wave and the active region inside the VCSEL cavity, with the wavenumber k_z and the relative shift Δz of the nodes and antinodes of the standing wave while changing the cavity length with the movable membrane. If an antinode of $|E(z)|^2$ overlaps with the active region, Γ_r has a maximum value of two. On the other hand, if a node

Structure name	Antireflection coating	Optical semiconductor length	Air gap length	Threshold	Tuning range
Extended Cavity (EC)	yes	$N_e * \lambda/2$		$\Leftrightarrow$	$\Leftrightarrow$
In Resonance (IR)	no	$M_c * \lambda/2$	$N_a * \lambda/2$	$\Downarrow$	$\Downarrow$
Off Resonance (OR)	no	$M_o * \lambda/2 - \lambda/4$	$N_a * \lambda/2$	$\Uparrow$	$\Uparrow$

Table 2: Tuning characteristics for different cavity designs. The characteristics are compared to the extended cavity design (EC) N_e, M_c, M_o, N_a are positive integers.

coincides with the active region, Γ_r becomes zero. Thus the tunable VCSEL needs to be designed in a way that an antinode overlaps with the active region for a maximum effective gain. The one dimensional longitudinal intensity distribution has been simulated considering every single layer and its refraction index of a given tunable VCSEL-design using the Matrix-Transfer-Method[4]. Fig. 11 shows that the intensity distribution has an antinode inside the gain region for an air-gap length of 11 μm. Due to the wavelength change the field distribution will shift and the overlap between gain region and field may become smaller. To minimize the damping of the optical field in absorbing layers such as the tunnel junction of our long wavelength VCSELs the standing wave should have additionally antinodes at those layers. These effects have to be considered when designing a tunable VCSEL.

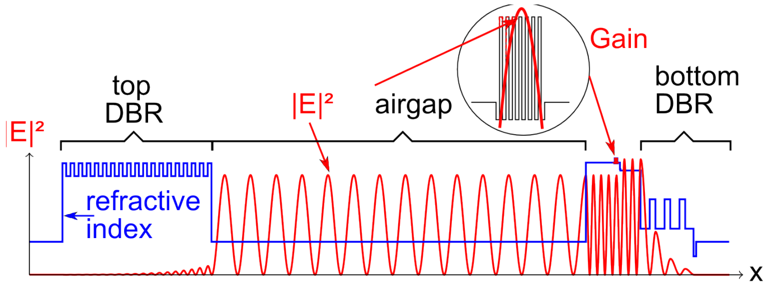


Figure 11: Simulation of the longitudinal 1D intensity distribution ($|E(z)|^2$) in a long-wavelength tunable VCSEL. The refractive index profile $n(z)$ is defined by the layer composition of the VCSEL. The blow-up shows that $|E(z)|^2$ has an antinode inside the gain region (quantum wells). The field will move to left or right while tuning.

One special feature not present in a standard non tunable VCSEL is the air gap. This gap has an essential influence on the tuning behavior of our tunable VCSEL. The additional reflection at the semiconductor air interface will influence as well the threshold as the achievable tuning range. In table 2 we summarize the properties of the investigated structures:

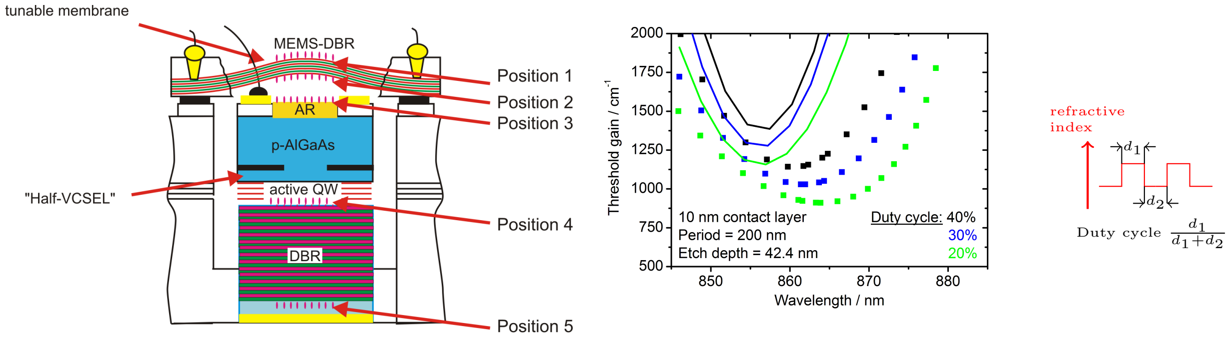
In the EC design the reflection at the air semiconductor interface is suppressed, thus the tunable VCSEL behaves as a standard VCSEL with a varying resonator length. The possible lasing wavelengths are primarily determined by the overall optical length thus the lasing wavelength is directly proportional to the air gap.

If we have no antireflection coating at the semiconductor air interface there is an additional reflectivity at this interface. The Bragg mirror and the interface form a Fabry-Pérot resonator which has a reflectivity varying with wavelength. In the IR design the reflected field from the mirror is in phase with the reflected field at the interface, that means the Fabry-Pérot resonator has a maximum reflectivity.Thus the overall reflected field becomes larger resulting in a smaller threshold. Due to the dependence of the phase of the reflection factor of the Fabry-Pérot on the wavelength the tuning characteristic shows a typical

S-shape [8], but the tuning range becomes smaller compared with the EC-design.

In the OR design, also called adapted design in literature [8], the reflected field from the tunable mirror and the field reflected by the interface have opposite phases resulting in a lower reflectivity and thus a higher threshold. In this case the phase dependence is adjusted in a way that the tuning range will be increased. Due to the higher threshold we postponed the realization of this approach for future research.

3.5 Polarization



(a) GaAs based tunable VCSEL

(b) threshold gain vs. λ

Figure 12: a) Investigated positions of the sub-wavelength grating

Since the VCSEL is axial symmetric there is no preferred direction for the state of polarization. If the symmetry would be ideal we would see two orthogonal modes with identical wavelengths, so called degenerated modes. In real VCSELs there is a small birefringence resulting in a small difference in wavelength for both modes. During operation, e.g. tuning or modulation, the state of polarization may change which can be a very disturbing property in special applications, such as communications. Therefore, we additionally developed tunable VCSEL with a sub-wavelength grating to assure a stable state of polarization during operation. Intensive modeling activities have been carried out, both to support the technological partners with design parameters and to improve the model capabilities of properly handling sub-wavelength gratings (SWG). Compared to previous devices [12, 9], where gratings were successfully used to fix polarization properties by positioning them at the outcoupling interface, in our structures there are many other possible positions. This is due to the two chip concept and to the presence of dielectric layers. In fact the grating is much more effective if it is placed where a strong index contrast is available. In Fig.12 such positions are put in evidence and numbered from top to bottom. The first two positions are located at the top and bottom sides of the top curved mirror, the third is at the cavity-air interface, 4 and 5 at the top and bottom side of the dielectric back mirror. As discussed before, all such positions display a strong index contrast: semiconductor-air, dielectric-air, semiconductor-dielectric, dielectric-gold. The selection of the location is a tradeoff between theoretical investigations and technological constraints. Although the theoretically optimal locations were at position 1 and 5, we had to chose position 2 for the InP based VCSELs and position 3 for the GaAs based devices. At those positions a very careful design of the grating parameters was necessary. As an example results for the optimization of the grating at position 3 for our short wavelength VCSEL are depicted in figure 12. These extensive theoretical investigations were necessary to achieve good results for the polarization stability.

3.6 Movable Bragg mirrors

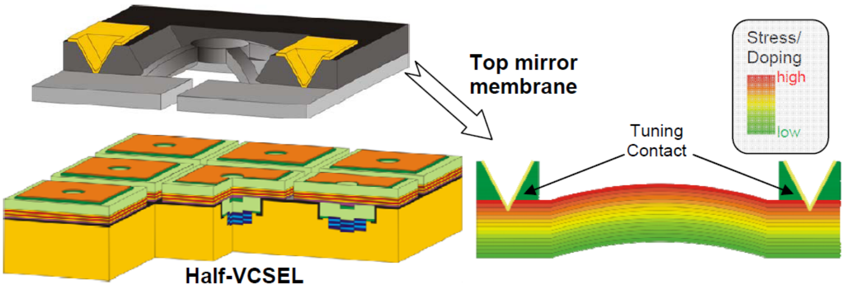


Figure 13: Sketch of the MEMS-VCSEL (left) and the structure of the mirror membrane. The red layers possess higher strain

The top tunable Bragg mirror should provide a high reflectivity ($> 99.5\%$) with a bandwidth as large as possible. Furthermore, an actuation of the mirror for tuning must be possible and a defined convex curvature is needed to reflect the Gaussian-shaped fundamental (transverse) laser-mode of the "Half-VCSEL". Therefore the fabricated mirrors have an implied stress and doping gradient to accomplish this task. Fig. 13. shows a schematic of the structure. We developed electromechanically tunable mirrors as well for the GaAs based short-wavelength VCSELs as for the InP based long wavelength VCSELs.

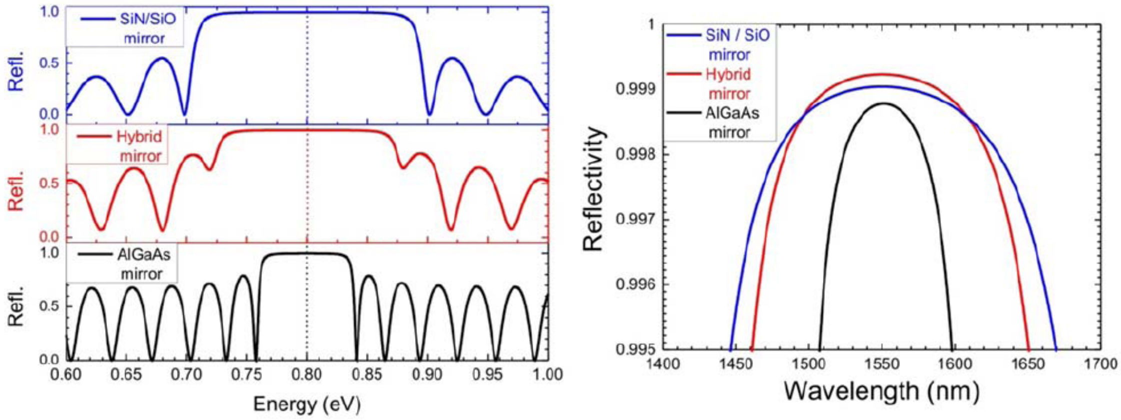


Figure 14: Calculated reflection of a dielectric (blue), hybrid (red) and semiconductor (black) Bragg mirror for 1.55μm central wavelength. The semiconductor DBR consists of 22.5$GaAs/Al_{0.85}GaAs$ pairs, the structure of the dielectric and hybrid mirror is described in the text.

For the fabrication of the tunable membranes a material is needed, whose conductivity and stress can be tailored and which shows only very small optical loss. The Al(In)GaAs material-system grown by MBE on GaAs substrates offers an sufficient high bandgap (to avoid fundamental absorption), it can be n-doped with Silicon and also the stress can be adjusted by adding Indium during the growth. The layers of the mirror membrane should exhibit a bandgap at least 100 meV larger than the lasing wavelength to avoid fundamental absorption.

For the short wavelength VCSELs emitting at a wavelength of 850 nm which corresponds to 1.46 eV we have to add 14% Aluminium to the GaAs to avoid strong absorption in the Bragg mirror. .

In case of the semiconductor mirrors $\mathrm{Al}_{0.85}$GaAs is used as the low-index material (this means it has a lower refractive index as GaAs). An Aluminium-content of 85% is chosen to prevent strong oxidation of the material, which would destroy the membrane. The achievable refractive index difference (Δn) of this material system is around 0.4 [1]. Besides semiconductors also dielectric materials such as SiO_2 and Si_3N_4 have been evaporated with a low temperature ($< 100^oC$) ICP-PECVD system. This material has a comparatively large bandgap, but no doping is possible, which means an extra thin metal-layer has to be applied on top to achieve electro-thermal or electro-static actuation. The great advantage of these dielectric layers is the big Δn of 0.5, which will be explained in the next section.

Important parameters and specifications:

The main principle of a Bragg mirror is the idea not only to use the reflexion at one interface (like semiconductor / air), but repeat it periodically in that way that the reflexion at the high and low refractive index material interfere constructively. A Bragg mirror usually starts and ends with the high index material and the thicknesses d of all layers have to match

$$d_{1,2} = \frac{\lambda_0}{4n_{1,2}} \tag{12}$$

Here λ_0 is the central wavelength of the Bragg mirror and n is the corresponding refractive index. The accurate growth of the DBR in terms of layer thickness is therefore mandatory for the fabrication. The reflexion bandwidth on the other hand is determined by the refractive index difference $|n_1 - n_2|$ as already mentioned. For the bandwidth $\Delta\omega$ follows [23]:

$$\Delta\omega = \frac{2\pi c}{\lambda_0} \arcsin\left(\frac{|n_1 - n_2|}{n_1 + n_2}\right) \tag{13}$$

where c is the speed of light.

For a tunable laser as the MEMS-VCSEL we can formulate the following ideal properties for the Bragg mirror:

- The middle of the reflexion bandwidth (λ_0) has to be at the central laser wavelength to achieve highest possible tuning and optimal device performance.
- The refractive index difference should be as large as possible to achieve high reflexion bandwidth and to reduce the penetration depth L_{eff} and therefore the cavity length, which results in a reduced free spectral range.

From these considerations we deduce that the layer thickness and the refractive index difference are the main parameters for the design and fabrication of the Bragg mirrors. In the SUBTUNE project three different types of Bragg mirrors have been realized: the semiconductor Al(In)GaAs-based, the so called hybrid Bragg mirror, which is combination of around 4.5 pairs of semiconductor material and 8 pairs of SiN/SiO, and the dielectric Bragg mirror, which consists of 11.5 pairs of SiN/SiO. Transfermatrix calculations of all three mirror types are shown in Fig. 14.

From Fig. 14 it is clearly to see that the reflexion bandwidth is strongly enhanced by using SiN/SiO instead of only AlGaAs. Regarding the desired specifications for the MEMS- VCSELs, which are shown in table 3, we can conclude, that only the hybrid and dielectric Bragg mirror can serve the needed bandwidth with a required reflectivity higher than 99.5% for "better" device performance as described in our specification table 3.

The main disadvantage of these "new" Bragg mirror concepts is that the processing and the fabrication of the membranes is more challenging compared to the standard semiconductor Bragg mirrors. Therefore at first always a semiconductor Bragg mirror is used to clarify if the integrated laser is working, then the new types are examined.

	Min. Perf.	Better Perf.	Laser wavelength (nm)
Tuning range (nm)	> 30	> 40	845
Central λ (nm)	820-880	840-860	
Tuning range (nm)	37	100	1555
Central λ (nm)	1555	1555	
Tuning range (nm)	34	60	2000
Central λ (nm)	1988	1980	

Table 3: List of the specification for tuning range and central wavelength

.

3.7 Fabrication

We developed two different technologies for the fabrication of the tunable VCSELs, bulk micromachining and surface micromachining. Both technologies were developed in both material systems: GaAs for short wavelength VCSELs and InP for long wavelength VCSELs.

Using bulk micromachining the movable top mirrors are fabricated in a separate process [14] and afterwards combined with the "Half-VCSEL" consisting of the active semiconductor and the bottom mirror. It has the advantage that both fabrication processes can be optimized separately and we are additionally very flexible in the choice of material and shape of the mirrors. But it has the disadvantage being very time consuming and not applicable for mass production and the achieved accuracy depends strongly on the manufacturing process.

In contrast, surface micromachined mirror membranes are fabricated directly on top of the "Half-VCSEL" and thus enable a cost-effective and reproducible mass production. Inside the SUBTUNE project we successfully demonstrated this technology for VCSELs operating at 850 nm and 1550 nm wavelength.

In the following we shortly describe the fabrication process of the active "Half-VCSEL" for both material systems and give a short overview on the manufacturing of the membranes.

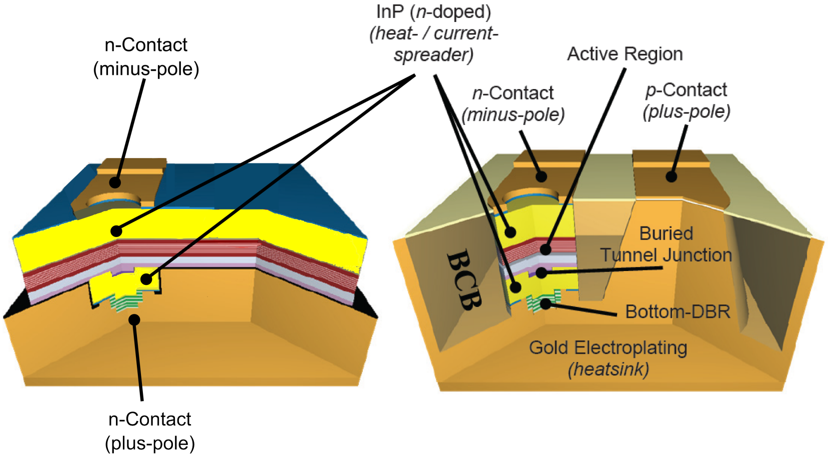


Figure 15: A schematic sketch of the 1550 nm "Half-VCSELs". Left hand side: "Half-VCSEL" aiming for low speed application, such as "FBG-sensing" and "Gas sensing". Right hand side: "Half-VCSEL" for high speed communications.

InP and GaAs based "Half-VCSELs" We grew many different InP based structures for the different applications envisaged.

The semiconductor cavity is made out of two n-type InP heat- and current spreading layers, sandwiching the compressively strained active region. The burried tunnel junction consists of two highly p^+ and n^+ doped lattice matched layers. The heat is extracted out of the device by the Au-substrate.

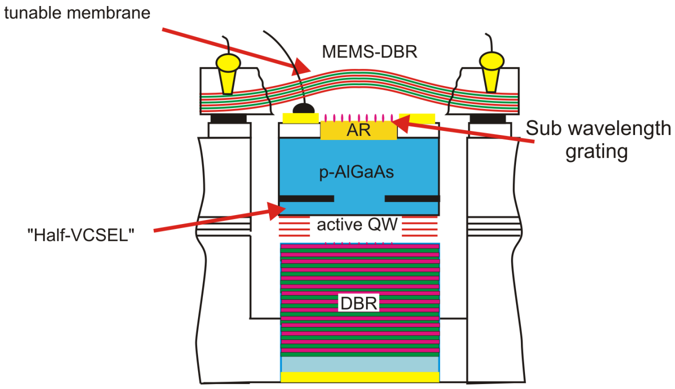


Figure 16: A schematic sketch of the 850 nm "VCSEL" equiped by a sub-wavelength grating.

Due to its tunnel junction the InP-based "Half-VCSEL" shows the big advantage of low ohmic resistance, since most of the low conducting semiconductor p-material can be exchanged by high conducting n-material due to the tunnel junction. This measure results not only in a much better high frequency behavior but it improves also significantly the thermal characteristics of the VCSEL.

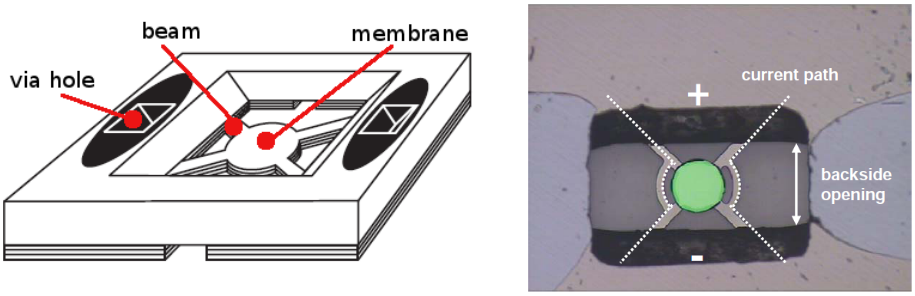
For an essential reduction of the capacitance of the device and therefore the parasitics, which is mandatory for high-speed modulation, most of the semiconductor material is now replaced by the low-k material BCB as seen on the right hand side of figure 15. This design together with the short cavity length allows the fabrication of very high speed VCSELs.

The structure of the short wavelength VCSEL based on the GaAs material system is depicted in figure 16. The GaAs-based "Half-VCSEL" comprises a bottom GaAs-GaAlAs Bragg mirror with high reflectivity, an active region for light amplification and an oxide aperture for current and light confinement. An intracavity top contact and and six highly doped layers reduce electrical resistance. Additionally we developed high speed devices where a 20 μm-wide trench decouples a small mesa from the large platform. The mesas are embedded with low k dielectric BCB, to reduce the capacity. Additionally this VCSEL is equipped with a 50 Ω microstrip line providing a very good high frequency input port.

Tunable membranes

Bulk micromachined membranes As already mentioned we are producing tunable membranes using bulk and surface micromachining. The main challenge for both technologies is the achievement of the correct geometry of the stable plane-concave resonator. Thus the length of the air gap and the curvature of the membrane has to be adjusted to the aperture and length of the "Half-VCSEL". Additionally an actuation scheme has to be implemented. For the bulk-micromachined membranes we used electrothermal actuation while for the surface-micromachined membranes as well electrothermal as electrostatic actuation was implemented.

The semiconductor DBR For the 1.5 μm consists of MBE-grown GaAs/$Al_{0.85}Ga_{0.15}As$ quarter wavelength layers with refractive index contrast of 0.39. The inclusion of the Indium content up to 5 % at the upper part of the mirror induces compressive strain, which then results in membrane deflection within



(a) Schematic sketch of membrane (b) Dielectric membrane

Figure 17: Bulk micromachined membrane[26]

the range of 8-12 μm (air-gap) and radius of curvature (RoC) within the range of 2-3 mm. The membrane parameters are measured with a confocal microscope which allows 3D structure imaging. Additionally, the DBR layers are doped with silicon during the epitaxy process to enable electrical conductivity and thus tuning of the membrane. To ensure electrical isolation between the laser and the mirror the final layers of the DBR remain undoped. A sketch of a typical bulk-micromachined membrane is given in figure 17. The tuning is achieved by driving a current through the beams, resulting in a temperature rise and thus in an elongation of the beams. This elongation is proportional to the dissipated electrical power and causes a change of the cavity length resulting in a wavelength tuning.

To cover the whole free spectral range (FSR) one needs around 1 μm movement range which can be reached within ≈ 1 ms time. Figure 18 shows the relation between the electrical current and the membrane deflection measured with the confocal microscope. The deflection is proportional to squared heating current $\sim I^2$. The resistance of the MEMS depends on membrane and beams dimensions and varies between R=0.5 kΩ and 1 kΩ. The structure heats up to about 100^{o}C while tuning.

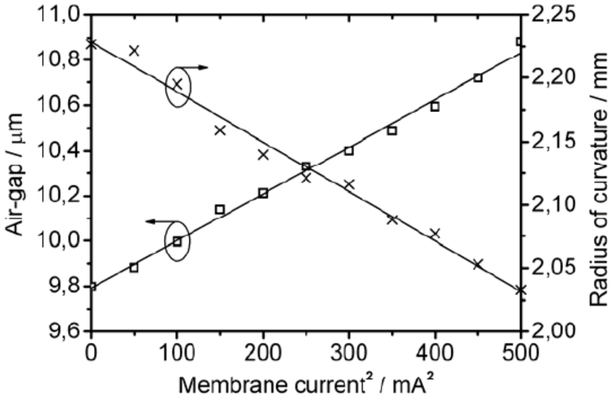


Figure 18: The air-gap and radius of curvature versus squared membrane current

Dielectric DBRs consist of alternating SiO/SiN layers deposited on GaAs substrate. The deposition of the dielectric layers are performed with plasma enhanced chemical vapor deposition (PECVD). The advantage of this dielectric material composition SiO/SiN is the high difference of the refraction index resulting in a fewer layers and a higher stop bandwidth compared with a semiconductor mirror with the same reflectivity.

Figure 19 depicts the simulated reflectivity spectrum of two DBRs, one consisting of dielectric and the other consisting of semiconductor material. Additionally the measurement of the dielectric DBR in the wavelength range from 1300 nm to 1650 nm is shown. By the simulation of these two different mirror materials it can be seen that the dielectric mirror has a much larger stop bandwidth with the same reflectivity as the semiconductor material.

The concave bending of the dielectric mirror membrane is realized with a mechanical stress inside the layers by changing the process parameters of the PECVD. Every process parameter as deposition pressure and temperature, gas flow ratio of the precursor, applied RF- power to the plasma has an influence on the stress of the layer. Empirically, the most influence on the stress has the deposition pressure and the gas flow ratio. Stress values in the range from around -700 MPa (compressive) to +80 MPa (tensile) can be realized. The heating of the beams and thus the tuning is achieved by sending a current through additionally deposited metallic lines on the membrane (see figure 17(b)).

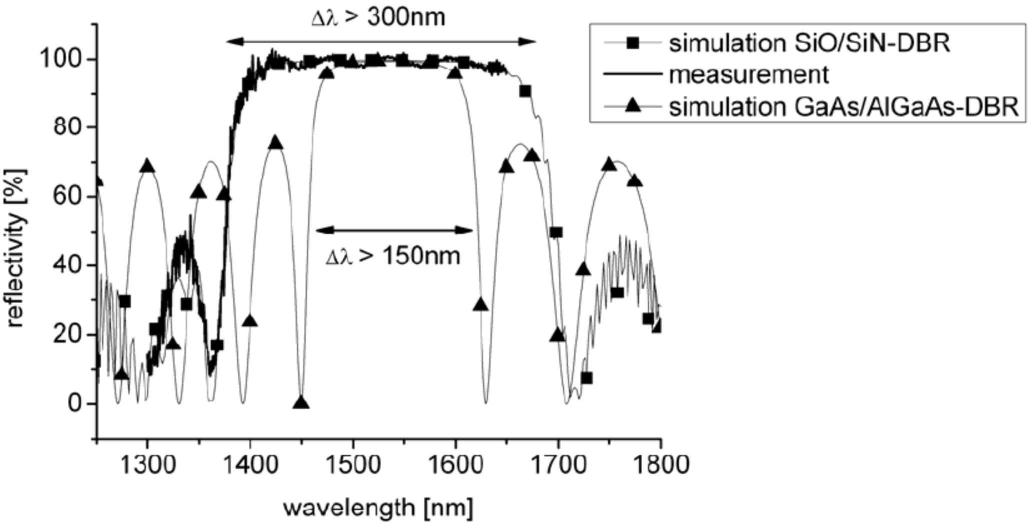
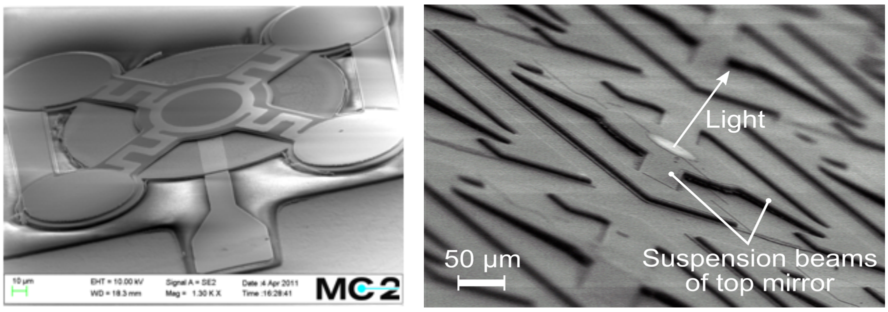


Figure 19: Measurement and simulation of semiconductor and dielectric mirror [13]

Hybrid membranes are made of semiconductor and dielectric materials. This gives a wide stop bandwidth and high reflectivity because of high refractive index difference between the dielectric layers. Additionally, having Si doped semiconductor layers, one can easily implement the electrical heater functionality. Hybrid membranes are fabricated in two deposition steps. During the first step, semiconductor layers are grown on GaAs substrate using the MBE process. Next, the dielectric layers are deposited by the PECVD process. Important issue is obtaining the stress compatibility of the two material systems processed by two different methods so that desired mirror deflection can be achieved (proper radius of curvature and air-gap).

Surface micromachined membranes We have developed two different fabrication technologies for surface micromachining using different kind of sacrificial layers. Our partner Chalmers uses a photoresist which is formed in a reflow process while at the TU Darmstadt a sacrificial layer made from Ni is used and structured by wet etching. In both cases a Bragg mirror is deposited on top of the sacrificial



(a) REM of surface micromachined tunable VCSEL based on GaAs fabricated by Chalmers

(b) REM of surface micromachined tunable VCSEL based on InP fabricated by WSI and TUD

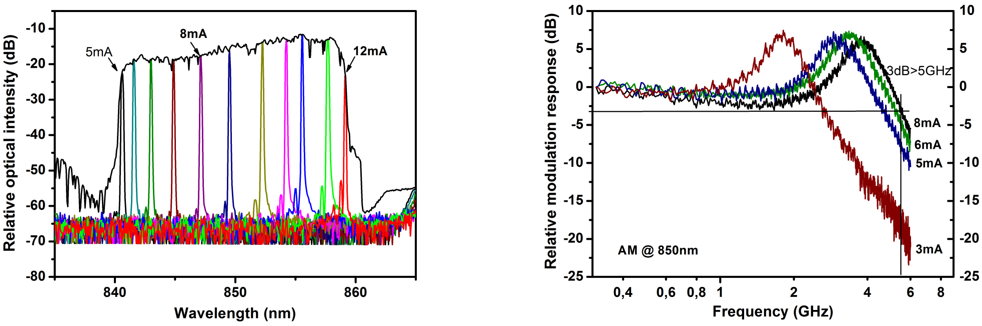
Figure 20: Surface micromachined membranes[16, 11]

layer. The mirrors are completed with a metallic layer for electrothermal tuning. After that the sacrificial layer is removed, the membrane is released and the tunable VCSEL can be supplied with contacts. The different technologies are described in detail in [16, 11]. In figure 20 REM-photos of the surface micromachined VCSELs for the short (a) and for the long wavelength (b) are depicted.

In figure 20 we can clearly see the membrane with its four beams, the meander of the heating contact on the beams and the four contact pads. Additionally we see the 50Ω line providing the high frequency signals to the VCSEL. On the right hand side we see a 1.5 μm surface micromachined wafer. It clearly seen that many tunable VCSELs can be produced on one wafer simultaneously.

3.8 Characterization

In this section we summarize only the outstanding results of the VCSELs developed during the SUBTUNE project.



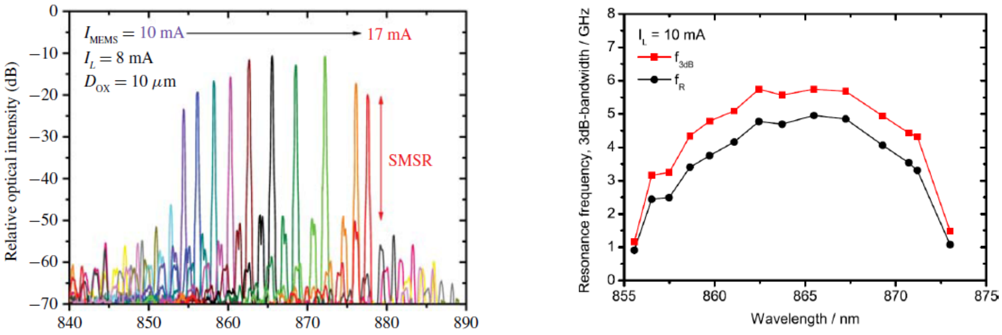
(a) Emission spectra for different tuning currents. The envelope shows the tuning range.

(b) Direct modulation of the VCSEL at different bias currents.

Figure 21: Bulk micromachined tunable GaAs based [7].

GaAs based VCSELs For the GaAs based VCSELs two types have been fabricated within this project. One type is based on the bulk micro-machining and the other one on surface micro-machining technologies. First we will focus on the bulk micro-machined short-wavelength VCSELs. The tunable 850 nm VCSEL is intended for wavelength division multiplexed (WDM) reconfigurable optical interconnects where transmission of data at Gbit/s rates is required. The challenging aspect of the work is to combine tunability over a sufficient range of wavelengths with sufficient high speed modulation capabilities of the VCSEL. The design of a GaAs-based "Half-VCSEL", intended for hybrid integration with an external movable mirror for wavelength tuning, has been optimized using 1D and 3 D optical simulations and 2D current simulations. A design for high speed modulation has also been implemented to enable the use of the tunable 850 nm VCSEL in its intended application: wavelength multiplexed, reconfigurable optical interconnects. First tunable VCSELs using this technology were fabricated and first tuning and modulation experiments were performed. They already showed a tuning range of 19 nm, an output power of 0,17 mW (see Fig. 21(a)) and modulation bandwidth larger than 5 GHz (see Fig. 21(b)).

The surface micro-machined VCSELs show a larger tuning range of 25 nm (see Fig. 22(a)) and modulation bandwidth, Fig. 21(b) shows the modulation bandwidth for a fixed laser bias of 10 mA at different wavelength.



(a) Emission spectra for different tuning currents. The envelope shows the tuning range.

(b) Resonance frequencies measured over the tuning range for a fixed laser bias current of 10 mA.

Figure 22: Surface micromachined tunable GaAs based [16, 19].

Polarization-stability of GaAs based VCSEL with SWG A sub wavelength grating (SWG) has been implemented into the bulk-micromachined short-wavelength VCSEL for polarization stabilization. Both polarizations are measured simultaneously for both, over the entire tuning range and for the current range at different wavelength. Fig. 23 shows, that the polarization is stable over the entire tuning range.

The polarization stability over the the laser current range has been measured with two power-meters (one for each polarization) behind a polarization splitting setup simultaneously. The measurements have been made exemplarily at two different wavelength and are shown in Fig. 24.

InP based bulk micro-machined VCSEL The best results have been achieved with a bulk micromachined VCSEL utilizing a hybrid mirror-membrane. The tuning range is 56 nm with a maximum output power of > 2 mW at 1554 nm. The laser shows excellent side-mode suppression ratios of 60dB. The modulation bandwidth of the laser has been evaluated for different laser bias currents with a maximum bandwidth of 6 GHz. The measurement results are summarized in Fig. 25.

Additionally the linewidth of the lasers has been investigated by measuring the delayed self heterodyned signal (DSH) of the tunable VCSEL. A minimum linewidth of 27 MHz has been measured, which

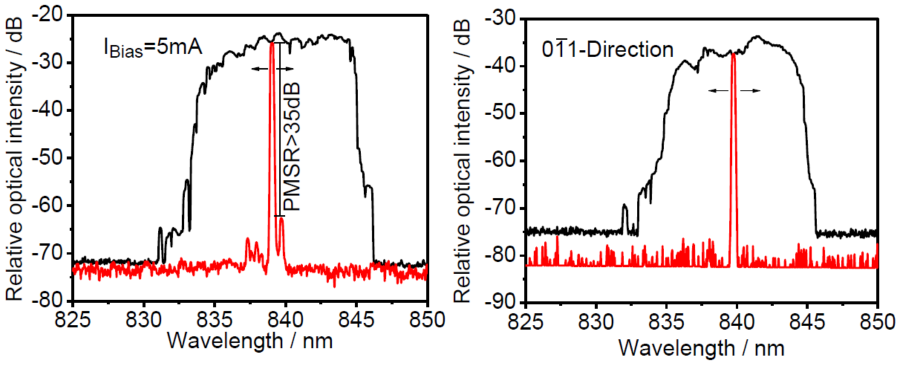


Figure 23: Measured tuning range without (left) and with polarization selective measurement setup (right). The tuning ranges do not differ which indicates, that the polarization is stable over the entire tuning range.[6]

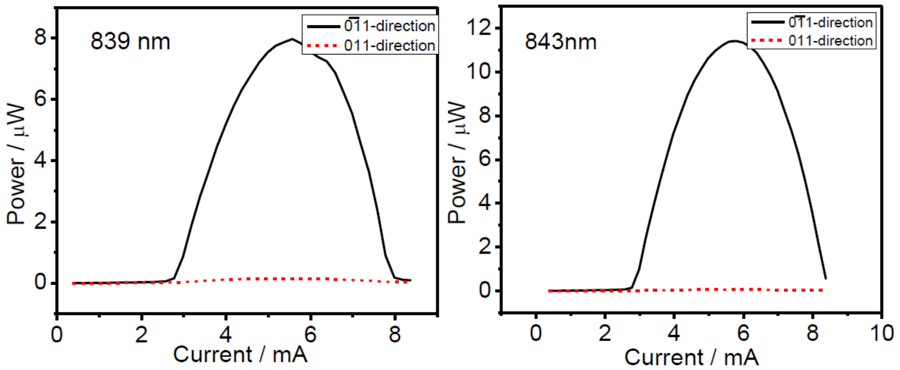


Figure 24: PI-characteristic of both polarization direction using the polarization setup, (left) At a wavelength of 839 nm, (right) at a wavelength of 843 nm[6].

is the smallest linewidth for tunable VCSEL in literature. The DSH signal is shown in Fig. 26. The linewidth can be directly extracted from the DSH signal by simply multiplying the width of the DSH signal with a factor of 1/2 if the signal has a Lorentz-shape, which is the case. The polarization stability was another very important issue of the project. Finally, a SWG has been implemented into the top mirror-membrane of a semiconductor DBR. Polarization measurements have been performed and it could be verified, that the implemented SWG stabilizes the emitted state of polarization over the entire tuning and current range, as it has been shown for the short-wavelength VCSELs, already. The two orthogonal polarization states have been coupled into a fibre which is connected to a polarizing beam splitter. The two fibre outputs of the splitter have been connected to two powermeters. The polarization is adjusted to the main axis of the beam splitter with a polarization controller placed in front of the beam-splitter. The setup is fully based in fibre optics.

The tuning range of the measured laser was > 20 nm and a PIV-curve was taken each 2 nm. No polarization switches have been observed over the tuning and current range which is shown in Fig. 27. The figure also shows an exemplary PIV-curve at 1545 nm. The power does not represent the output

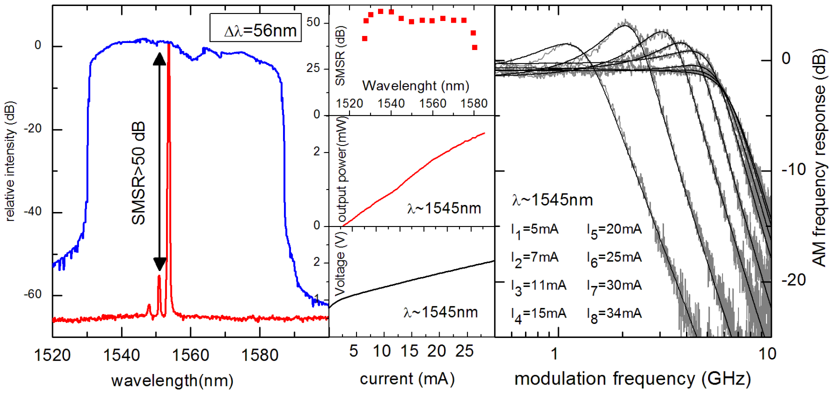


Figure 25: Characterization summary of the bulk micro-machined InP VCSEL utilizing a hybrid mirror-membrane.[24]

power of the laser, since the measurement setup has quite high losses. It is intended for measuring the polarization stability only. A direct power measurement (coupling into multi-mode fibre) shows a world record output power of > 4 mW. Furthermore, it is noteworthy that the polarization mode suppression ratio is > 20 dB as it is shown in Fig. 27. This is due to the fact, that a perfect alignment of the polarization mode to the main axis of the splitter is not possible and the angle between both axes the smaller the suppression ratio.

InP based surface micro-machined 1550 nm VCSEL Here we show the best achieved results for surface micro-machined VCSELs. The measurement results are summarized in Fig. 28. The VCSEL starts lasing at 1584 nm and is tuned to 1606 nm with a heating power of 0.6 mW. At this point the next longitudinal mode starts lasing at 1504 nm. For 0.6 mW to 3 mW heating-power, the wavelength

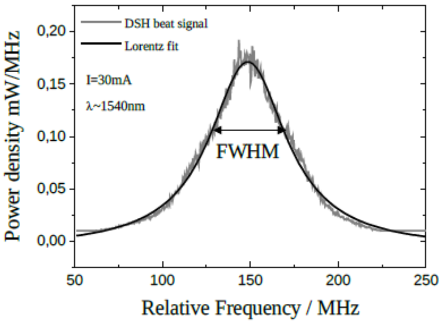


Figure 26: Delayed self heterodyne signal of an InP bulk micro-machined VCSEL. The VCSEL shows a minimum linewidth of 27 MHz.[24]

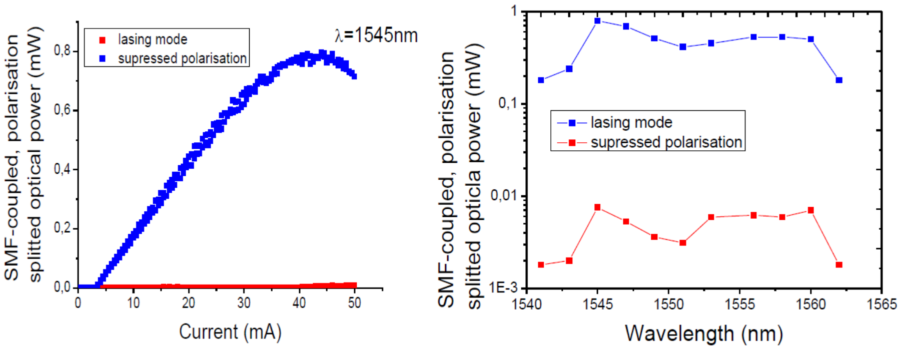


Figure 27: Maximum output power for the lasing mode and for the suppressed polarization mode achieved from the PI-characteristics measured for different wavelengths (ca. every 2nm).

is continuously tuned over 102 nm which is the largest single-mode tuning range reported in literature for tunable VCSELs. The measurements are in good agreement with the 2D simulations (done by CNR Torino). The tuning range is limited by the FSR of 102 nm. The FSR can be increased by further reducing the initial air-gap length. The implemented BTJ and the optimal adapted geometry of the top mirror provide an SMSR > 45dB over the entire tuning range. At 1550 nm, the thermal roll-over occurs at a laser current of 27 mA at which the output-power is 3.5 mW. The threshold current is at 2.3 mA. The laser has an output power > 2 mW over the entire tuning range. It is noteworthy that at a laser current of only 5 mA the tuning range still exceeds 82 nm. In this case, the tuning range is not limited by the FSR but due to an increase of the threshold current at the edges of the tuning range.

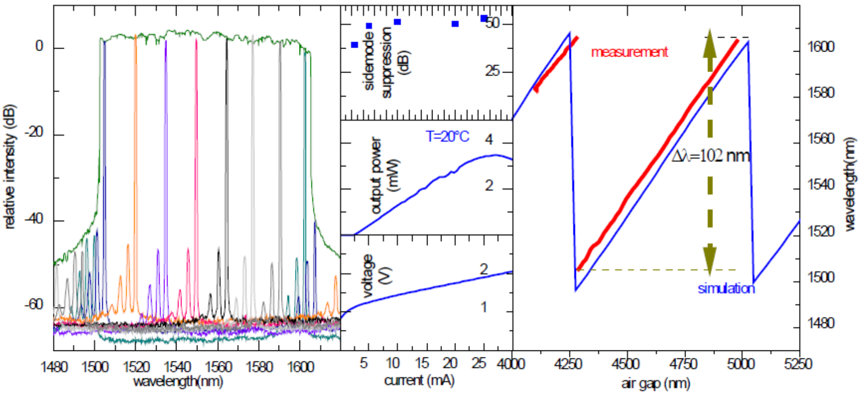


Figure 28: Maximum output power for the lasing mode and for the suppressed polarization mode achieved from the PI-characteristics measured for different wavelengths (ca. every 2nm).[11]

An advantage of the surface micro-machining technology, as it has been developed within this project, is that the wavelength can be tuned electro-thermally as well as electro-statically.

For electro-static tuning, a bias voltage is applied between the electrode on top of the membrane (actuation circuit) and the Laser top-contact. The resulting electro-static force acting on both electrodes decreases the air-gap length thus shifting the wavelength to lower values (not to higher values as it was the case for electro-thermal tuning). The electro-static tuning has been demonstrated on a tunable VCSEL without anti-reflection coating, which typically have smaller tuning ranges due to a smaller free spectral range (caused by the cavity coupling). The length of the enclosed air-gap, therewith the cavity length and thus the resonance wavelength of the cavity are proportional to the square of the voltage V ($\propto V^2$). The voltage V is applied between the top and bottom electrode. Electrostatic forces attract both electrodes and move the mirror membrane towards the fixed electrode at the surface of the "Half-VCSEL". The emission spectra for different tuning voltages and the tuning range as the envelope of the tuned laser peak are given in Fig. 29. The laser current is constant at 27 mA (thermal rollover) and the voltage at the VCSEL is 1.8 V. The temperature is stabilized at 20 ^{o}C. The envelope of the tuned laser peak shows a tuning range of 74 nm. A single emission spectrum is highlighted to determine the FSR which is 74 nm as well. Thus the FSR is the limiting factor of the tuning range only. The FSR can be further increased by implementing an anti reflection coating on the interface between "Half-VCSEL" and air-gap, as it has been demonstrated. The spectra show SMSR > 40 dB over the entire tuning range. The wavelength of the emission peak as a function of the applied voltage is shown in Fig. 30. Mode hop free single mode tuning over 74 nm is achieved with voltages between 110 V and 190 V. A minimal threshold current of 3 mA is demonstrated at a wavelength of 1520 nm with an optical output power of 1.8 mW at the thermal rollover for a driving current of 27 mA (see Fig. 31). To determine the modulation bandwidth

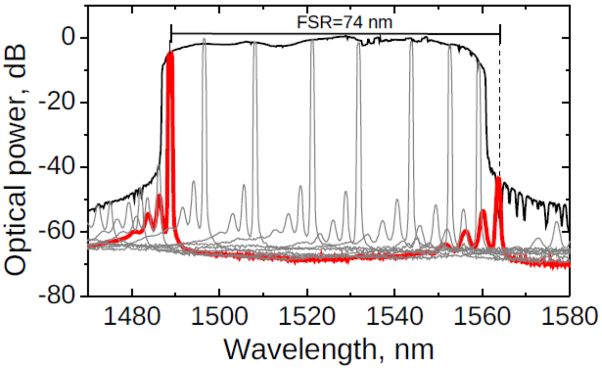


Figure 29: Emission spectra for different tuning voltages and the tuning range as the envelope of the fundamental laser peak. The laser current is 27 mA and the VCSEL is stabilized at 20 ^{o}C.[10]

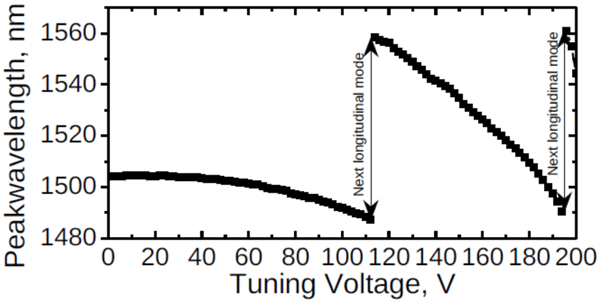


Figure 30: Measured wavelengths for different tuning voltages. The emitted wavelength is continuously tuned over 74nm.[10]

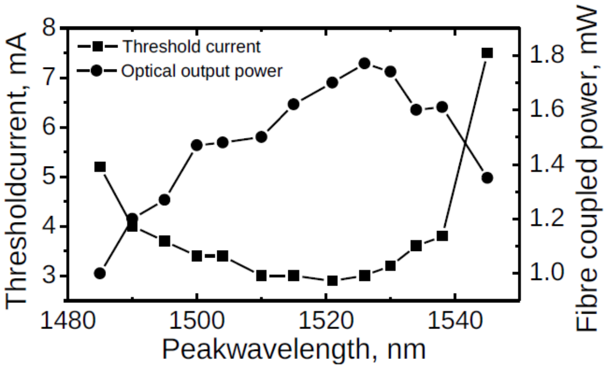


Figure 31: Threshold current and output power at the thermal roll-over as a function of the emission wavelength.[10]

for wavelength tuning, the tuning voltage is modulated with a sinus (peak to peak voltage Vpp=20V and offset voltage of V0=130V). The covered tuning range is measured with the OSA and plotted as a function of the modulation frequency in Fig. 32. Mechanical resonance frequencies are observed at 215 kHz and 1.23 MHz. Thus the laser wavelength can be modulated up to 215 kHz, since the first mechanical resonance frequency is the limit for electro static wavelength tuning.

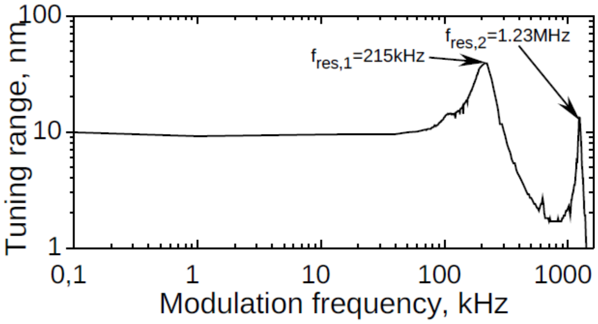


Figure 32: electro static frequency response of the tunable VCSEL. A sinusoidal a.c. modulated tuning voltage is applied to both electrodes (peak to peak voltage 20 V and an offset voltage of 130 V). The measurement shows two mechanical resonances at 215 kHz and 1.23 MHz, respectively.[10]

InP based surface micro-machined 2000 nm VCSEL Fig. 33 (left) shows the emission spectra of the tunable VCSEL for different heating-powers. The laser covers a continuous wavelength tuning range of 50 nm (from 1920 nm to 1970 nm) with side-mode suppression-ratio (SMSR) > 50 dB within the whole tuning range. The light-current-voltage diagram for the wavelength $\lambda = 1960nm$ is shown in Fig. 33 (right). The output power at thermal rollover is 0.83 mW. The threshold current and voltage is 5.5 mA and 1 V, respectively. The output power at the thermal rollover and the threshold current for different wavelengths are shown in Fig. 34. The maximum measured optical power is 1 mW. The threshold current is 2.5 mA. For determining the tuning-speed the heating current in the MEMS is modulated with a sinus function and the available tuning range is sampled with an optical spectrum analyzer. At higher frequencies, the thermal response cannot follow anymore and a static heating remains inside the MEMS

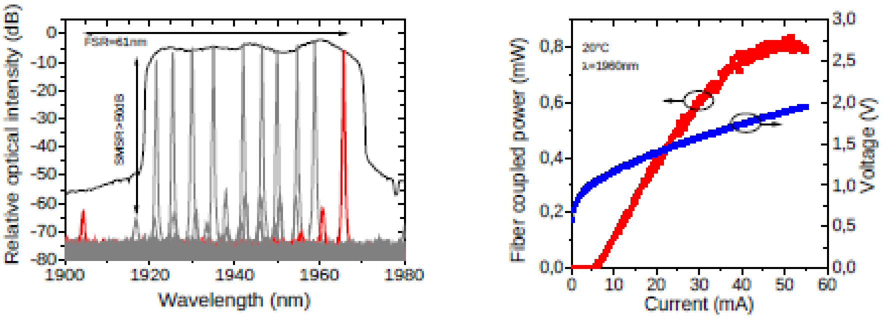


Figure 33: (left) emission spectra for different tuning voltages and the tuning range as the envelope of the fundamental laser peak. The laser current is 20 mA and the VCSEL is stabilized at 20 ^{o}C. (right) voltage (blue) and fibre coupled optical-power (red) over the driving current of the VCSEL at 1960 nm and 20 ^{o}C.[25]

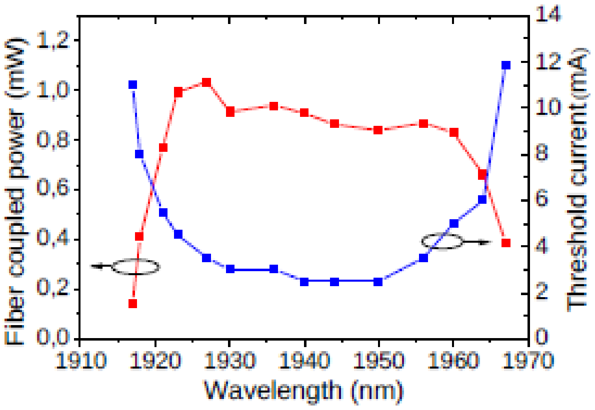


Figure 34: The blue curve shows the threshold current of the VCSEL and the red curve the VCSELs measured output-power at thermal roll-over for different wavelengths.[25]

(the tuning range converges towards the central wavelength, Fig. 35 (left)). The laser is biased with a DC current of 20 mA. The maximum current of the DBR-membrane needed for the entire tuning range is 32 mA. The DC tuning range is 50 nm; at the characteristic 3 dB-frequency of 110 Hz the MEMS-VCSEL still covers 25 nm (Fig. 35 (right)). All measurements are performed at room temperature T=20^{o}C.

3.9 Application

In the end of the project, the surface micro-machined lasers have been implemented and tested in a telecommunication environment. The MEMS-VCSEL is externally modulated at 10.3 GBit/s ($2^7 - 1$ pseudorandom bit sequence) using a reflective-electroabsorption modulator-semiconductor optical amplifier (R-EAM-SOA). The width of the transmission channels has been chosen to be narrower than the 50 GHz ITU grid. So the first issue was to guarantee a stable wavelength. Since the VCSEL was not packaged (on-wafer measurement) a slow wavelength drift could be obeserved (see Fig. 36a). This drift was compensated implementing a feedback loop using the tuning current of the MEMS to stabilize the

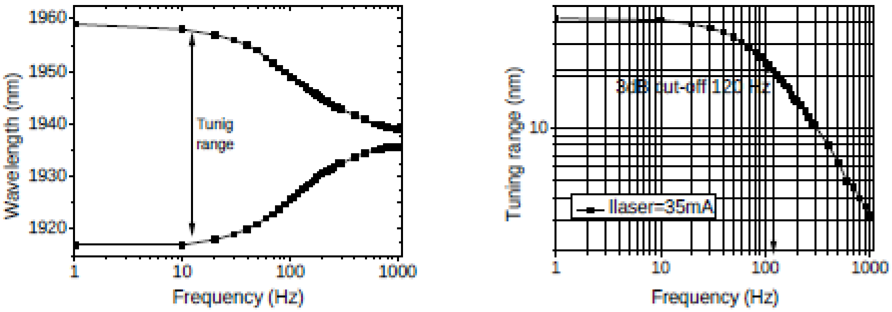


Figure 35: Electro thermal modulation of a tuneable VCSEL. (Left) with increasing actuation frequency, the boundaries of the tuning range converge towards the central wavelength, (right) the 3dB cut-off frequency of 120 Hz.[25]

wavelength within the appropriate transmssion channel. The VCSEL shows 10 GBit/s error-free data transmisson over 50 km singlemode fibre and a tuning range of 30 nm. The tuning range was not limited by the VCSEL (this device has a tuning rage of > 80 nm), but the bandwidth of the R-EAM-SOA. The bit error rate is compared with back to back (BTB) measurements and using a commercial ANDO AQ8201-13 external cavity laser (ECL). The externally modulated MEMS-VCSEL consistently achieves bit error rates of less than 10^{-9} across a 30 nm wavelength tuning range with only a small average receiver penalty of approximately 0.2 dB between the VCSEL and the ECL in both the BTB and 50 km cases (see Fig. 37).

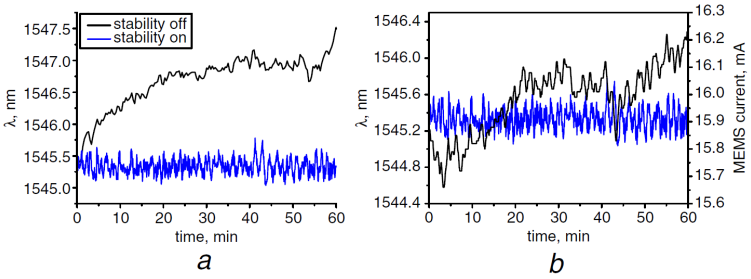


Figure 36: Emitted wavelength with and without wavelength stabilisation (a) and the change in MEMS-current to keep the wavlength within the set channel over 1 hour (b).

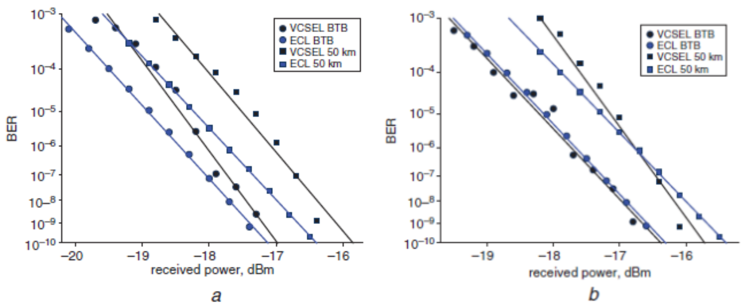


Figure 37: Bit error rate measurement results at two different wavelengths:(a) 1540 nm and (b) 1570 nm.

References

[1] M. A. Afromowitz. “Refractive index of $Ga_{1-x}Al_xAs$”. In: *Solid State Commun.* 15 (1974), pp. 59–63.

[2] T. C. Bond et al. “Photonic MEMS for NIR in-situ Gas Detection and Identification”. In: *Proc. IEEE Sensors.* LLNL. 2007, pp. 1368–1371. DOI: `10.1109/ICSENS.2007.4388666`.

[3] J. Buus and E.J. Murphy. “Tunable Lasers in Optical Networks”. In: *IEEE J. Lightwave Technol.* 24 (2006), pp. 5–11.

[4] JK. Chilwell and Hodgkinson I. “Thin-film field-transfer matrix method of planar multilayer waveguides and reflection from prism-loaded waveguides”. In: *J. Opt. Soc. Am. A1* (1984). SIMULATION, pp. 742–753.

[5] L.A. Coldren and Corzine S.W. *Diode Lasers and Photonic Integrated Circuits.* FUNDAMENTALS. New York: John Wiley & Sons Inc., 1995.

[6] H. A. Davani et al. “Polarization investigation of a tunable high-speed short-wavelength bulk-micromachined MEMS-VCSEL”. In: MOEMS. 2012, DOI: `10.1117/12.908262`. URL: `http://link.aip.org/link/PSISDG/v8276/i1/p82760T/s1&Agg=doi`.

[7] H.A. Davani et al. “Widely Electro Thermal Tunable Bulk-Micromachined MEMS-VCSEL Operating Near 850nm”. In: *IQEC/CLEO, 2011.* MOEMS. 2011.

[8] P. Debernardi et al. “Modal Properties of Long-Wavelength Tunable MEMS-VCSELs With Curved Mirrors: Comparison of Experiment and Modeling”. In: *Quantum Electronics, IEEE Journal of* 44.4 (2008). MOEMS, pp. 391–399. DOI: `10.1109/JQE.2007.914773`.

[9] P. Debernardi et al. “Reliable polarization control of VCSELs through monolithically integrated surface gratings: a comparative theoretical and experimental study”. In: *IEEE J. Select. Topics Quantum Electronics* 11 (2005). LASERTHEORIE, pp. 107–116.

[10] C. Gierl et al. “Surface micromachined MEMS-tunable VCSELs with wide and fast wavelength tuning”. In: *Electronics Letters* 22 (2011). MOEMS, pp. 1242–1243.

[11] C. Gierl et al. “Surface micromachined tunable 1.55 μm VCSEL with 102 nm continuous single-mode tuning”. In: *Optics Express* 19 (Aug. 2011). MOEMS, p. 17336. ISSN: 1094-4087. DOI: `10.1364/OE.19.017336`. URL: `http://www.opticsinfobase.org/abstract.cfm?URI=oe-19-18-17336`.

[12] A. Gustavsson Haglund et al. “High-power fundamentalmode and polarisation stabilised VCSELs using sub-wavelength surface grating”. In: *Electronics Letters* 41 (2005). VCSEL Grating, pp. 805–807.

[13] Sandro Jatta. “Plasmaunterstützte Abscheidung von dielektrischen Schichten zur Entwicklung von mikromechanisch abstimmbaren optischen Komponente”. SUBTUNE. PhD thesis. TU Darmstadt, 2011.

[14] S. Jatta et al. “Bulk-Micromachined VCSEL At 1.55 μm m With 76-nm Single-Mode Continuous Tuning Range”. In: *Photonics Technology Letters, IEEE* 21.24 (2009). MOEMS, pp. 1822–1824. DOI: `10.1109/LPT.2009.2034272`.

[15] V. Jayaraman et al. “OCT imaging up to 760 kHz axial scan rate using single-mode 1310nm MEMS-tunable VCSELs with $>$ 100nm tuning range”. In: *Proc. Conf. Lasers and Electro-Optics (CLEO)*. PRAEVIUM. 2011, pp. 1–2.

[16] B. Koegel et al. “Integrated MEMS-Tunable VCSELs Using a Self-Aligned Reflow Process”. In: *Quantum Electronics, IEEE Journal of* 48.2 (2012). SUBTUNE, pp. 144–152. DOI: `10.1109/JQE.2011.2172191`.

[17] B. Koegel et al. “Micromechanically Widely Tunable VCSEL for Absorption Spectroscopy at Around 1.55 μm”. In: *Optical MEMS and their Application Conference*. MOEMS. Big Sky, USA, 2006, pp. 7–8.

[18] B. Koegel et al. “Simultaneous Spectroscopy of NH3 and CO Using a >50nm Continuously Tunable MEMS-VCSEL”. In: *IEEE Journal of Sensors and Actuators* (2007). MOEMS.

[19] A. Larsson et al. “High-speed tunable and fixed-wavelength VCSELs for short-reach optical links and interconnects”. In: SUBTUNE. 2012, DOI: `10.1117/12.910261`. URL: `http://link.aip.org/link/PSISDG/v8276/i1/p82760H/s1&Agg=doi`.

[20] P. Meissner et al. “Micromachined Two-Chip WDM Filters with stable half symmetric cavity and their system integration”. In: *52nd Electronic Components and Technology Conference*. MOEMS. San Diego, May 2002.

[21] J. Rausch et al. “Experimental comparison of piezoresistive MEMS and fiber Bragg grating strain sensors”. In: *Sensors, 2009 IEEE*. MOEMS. 2009, pp. 1329–1333. DOI: `10.1109/ICSENS.2009.5398407`.

[22] A. E. Siegman. *Lasers*. Stanford. University Science Books, 1986.

[23] P. Yeh. *Optical waves in layered media*. New York: John Wiley & sons, 1988.

[24]]K. Zogal et al. “1.55-μm high-speed MEMS-tunable VCSEL”. In: *SPIE Photonics West*. Vol. no 8276-26. MOEMS. San Francisco, USA, 2012.

[25] K. Zogal et al. “Singlemode 50 nm Tunable Surface Micro-Machined MEMS-VCSEL Operating at 1.95μm”. In: *SPIE Photonics West*. MOEMS. 2012.

[26] K. Zogal et al. “Tuning dynamics of a $>$ 70 nm continuously tunable MEMS-VCSEL with a hybrid curved mirror”. In: *The European Conference on Lasers and Electro-Optics (CLEO/Europe) Munich, Germany*. MOEMS. 2011.

4 Impact and main dissemination activities

4.1 Market impact

Tunable lasers are key components in many applications including communication, (TDSL) tunable laser spectroscopy, fiber Bragg grating sensing, medical applications , etc. In communications for example the demand on network capacity showed an exponential increase during the last years driven by market trends such as large data centers, cloud computing and voice over internet protocol applications. One reason behind this network is the rising popularity of smart phones with all its new applications in social networking. In those networks tunable lasers supporting the increase in capacity through dynamic reconfigurability are essential.

Tunable VCSELs have the advantages to offer a continuous mode hop free tunability, having a small form factor and low power consumption. Additionally, the in the frame of the SUBTUNE project developed technology allows a cost effective on wafer mass production of these components. The same properties are essential for the implementation of tunable VCSELs in fiber Bragg grating sensing systems since both applications are using the same wavelength range. There is a very promising synergy for the component manufacturer using the same technology for the production of tunable lasers for both market segments.

The technology developed inside the SUBTUNE project can be expanded to different wavelength ranges, which was already proven by the demonstration of tunable VCSELs at 850 nm aiming for the application in reconfigurable cross-connects and for tunable VCSELs at 2000 nm for the implementation in multiple gas sensing systems.

4.2 Social impact

The result of the SUBTUNE project will help enabling a real all-integrating broadband network. It will especially provide components for the deployment of connectivity to residential users with no significant bandwidth limitations. Using the functionality of our developed lasers the telecom companies may provide bandwidth by demand to their customers, supporting the whole diversity of applications we know today or which will arise during the next years.

The broad tuning range of the VCSEL developed in this project offers the possibility to detect several gases using a single laser, which simplifies the setup of the sensor and enables further cost reduction. This technology will help to improve measurement systems necessary in environmental monitoring.

Many physical parameters such as temperature, strain, pressure, acoustic vibrations or wear can be measured using a fiber Bragg grating based transducer system. They are used in may application fields such as: civil engineering, composite materials, smart structure monitoring, oil & gas installations and also transportation (aircraft, train and ship monitoring). Due to the broad continuous tuning range the VCSEL will induce significant improvements such as measurement frequency and number of quantities, which can be measured simultaneously.

4.3 Contact details

SUBTUNE consortium	SUBTUNE website: http://www.subtune.org
Technische Universität Darmstadt	**Microwave Engineering and Photonics** http://www.imp.tu-darmstadt.de/imp/startseite_imp/index.de.jsp **Reference person:** Peter Meissner Phone: +49 6151 16 2462 Fax: +49 6151 16 4343 Email: meissner@imp.tu-darmstadt.de **Reference person:** Franko Küppers Phone: +49 6151 16 75060 Fax: +49 6151 16 4343 Email: kueppers@imp.tu-darmstadt.de
Chalmers Tekniska Hoegskola AB	**Microwave Engineering and Photonics** http://www.chalmers.se/mc2/EN/laboratories/photonics-laboratory **Reference person:** Anders Larsson Phone: +46 31 772 15 Fax: +46 31 772 8498 Email: anders.larsson@chalmers.se
University College Cork National University of Ireland	**Photonics** http://www.tyndall.ie/content/photonics-0 **Reference person:** Brian Corbett Phone: +35 3214904380 Fax: +35 3214904058 Email: brian.corbett@tyndall.ie
Technische Universität München	**Walter Schottky Institut** http://www.wsi.tum.de/Research/AmanngroupE26/tabid/97/Default.aspx **Reference person:** Markus-Christian Amann Phone: +49 89 289 1278 Fax: +49 89 320 6620 Email: mcamann@wsi.tum.de
VERTILAS	**VERTILAS** http://www.vertilas.com **Reference person:** Markus Ortsiefer Phone: +49 89 54842007 Fax: +49 89 54842019 Email: ortsiefer@vertilas.com
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	**CEA LIST** http://www-list.cea.fr **Reference person:** Pierre Ferdinand Phone: +33 1 69088339 Fax: +33 1 69088395 Email: pierre.ferdinand@cea.fr
CONSIGLIO NAZIONALE DELLE RICERCHE	**CONSIGLIO NAZIONALE DELLE RICERCHE** http://www.ieiit.cnr.it **Reference person:** Pierluigi Debernardi Phone: +39 011 5645420 Fax: +39 011 5645429 Email: pierluigi@polito.it
LEISTER PROCESS TECHNOLOGIES	**8. LEISTER PROCESS TECHNOLOGIES** http://www.leister.com/de/leister-switzerland.htm **Reference person:** Michel Studer Phone: +41 41 662 7621 Fax: : +41 41 662 75 25 Email: michel.studer@leister.com

4.4 Dissemination activities

The main dissemination activities were:

- Publication of scientific papers
- Participation at conferences
- Organizing a midterm workshop
- Internet dissemination

4.4.1 Scientific papers

The project published 15 papers in peer reviewed journals (IEEE journal of Quantum Electronics, Electronic Letters, Optics Express, IEEE Journal Selected Topics Quantum Electronics, Photonics Technology Letters, Plasma Processes and Polymers, Sensors, Applied Physic Letters, Frequenz). Refer to section A1 for a complete list.

4.4.2 Participation at conferences

We presented our results in 44 talks at international and national conferences, four of those talks were invited talks. Refer to section A2 for complete list.

4.4.3 Other communications

Partner Reports

TUD	A. Extance ”Wanted: applications for tunable VCSELs” compoundsemiconductor.net Jul. 2008 (http://compoundsemiconductor.net/cws/article/news/35166)
TUD	”Hybrid VCSEL set new tunability benchmark” fibresystems.org, Jul. 2008 (http://fibresystems.org/cws/article/news/35231)

4.4.4 Special Conferences: ”Future in Light” and ”VSCEL Days”

In 2009, in the frame of the 125th birthday of the international society SEE (Society of Engineers in Electricity, Electronics, and Information and Communication Technologies), under the High Patronage of the President of the French Republic, Nicolas Sarkozy, and with the support of the General Director of Supélec and the President of the SEE, Mr Alain Bravo, Supélec, ”grande école” of electrical engineering in France, organizes the international conference:

”**A Future in Light - Vision d'Avenir**” in its Metz Campus. Internet link is as follows: http://www.metz.supelec.fr/afutureinlight/.

Special conferences: VCSEL DAYS

The VCSEL Day is the meeting of all VCSEL and VECSEL related projects in the European framework programs FP6 and now FP7. The intention of such event is to initiate and maintain close contacts between the projects and form a European VCSEL/VECSEL network. The meetings gave the European VCSEL community the very appreciated chance to exchange information between the different projects and to intensify the scientific interaction.

In April 2009, VCSEL Day 2009 held at our partner Chalmers Univ. of Technology in Gothenburg, Sweden

(ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/photonics/photonics-newsletter-2009-april_en.pdf).

There were about 40 participants and more than 20 presentations. The meeting was very much appreciated by everybody and most European VCSEL and VECSEL projects were represented (HELIOS, MOSEL, NEMIS, SUBTUNE, VERTIGO, VISIT).

SUBTUNE was represented by four project partners (13 attendees coming from the project). SUBTUNE presentations were as follows:

- P. Meissner SUBTUNE: "Introduction and overview"
- T. Gründl "Design and technologies of high speed half-VCSEL based on InP"
- A. Larsson "Design and technologies of high speed half-VCSEL based on GaAs"
- K. Zogal, H. Davani "Bulk-micromachined and integrated tunable VCSELs"
- P. Debernardi "Tunable VCSEL design by VELM simulations"

In 2010, the VCSEL-day was organized by our partner IEIIT-CNR, Politecnico di Torino, in Torino, Italy, 6-7 May 2010. The workshop takes place on one day basis (7th May).

This meeting offers the opportunity for informal presentations of projects and recent achievements. Participants in the following ongoing FP6 and FP7 projects attended the event:

- NEMIS (New mid-IR sources for photonic sensors),
- SUBTUNE (Widely tunable VCSELs using sub-wavelength gratings),
- VISIT (Vertically integrated systems for information transfer),
- GIGAWAM (Gigabit access passive optical network using WDM).

SUBTUNE project was represented by several partners, and SUBTUNE-related presentations were done at this event, as follows:

- P. Meissner , "The SUBTUNE project: Widely tuneable VCSELs"
- K. Zogal, "Different concepts for MEMS tuneable VCSELs"
- B. Kögel, "Short-wavelength tunable VCSELs"
- A. Haglund, "High-speed 850 nm VCSELs"
- T. Gründl, "BCB encapsulated VCSEL based on InP suitable for MEMS Technology"
- B. Corbett, "Excitation and manipulation of surface plasmons using VCSELs"
- M. Ortsiefer, "Recent progress of InP-based long-wavelength VCSELs for communications and sensing applications"
- M. C. Amann, "Recent progress on GaSb-based single-mode VCSELs".

In 2011, the VCSEL-day takes place in Toulouse-France (http://conf.laas.fr/VCSELday/venue.html).

- K. Zogal, "High Speed Modulation of a 1.55-μm MEMS-Tunable VCSEL"
- M. Ortsiefer, "Recent Progress of InP-based Long-Wavelength VCSELs for Communications and Sensing Applications"
- P. Meissner, "Strategy for the development of tunable VCSELs"

- B. Kögel, "Integrated MEMS-Tunable VCSELs Using a Self-Aligned Reflow Process"
- C. Gierl, "102 nm Continuous Single-Mode Tuning with a Surface Micro-Machined tunable VCSEL"
- P. Debernardi, "Collimating VCSEL light by integrated microlenses: comparison of experiment and modeling"
- B. Corbett, "Voltage spectroscopy of long wavelength VCSELs under optical injection"

4.4.5 Public Midterm workshop

Objectives of the mid term event where as follows:

1. Project review with the European Commission (Scientific Officer),
2. Presentation of main results to the VCSEL community
3. Enhanced feedback from the VCSEL community concerning SUBTUNE technologies
4. The same feedback enhancement concerning the tuneable VCSELs applications
5. Help the SUBTUNE consortium to manage the second half part of the project
6. Provide input for Dissemination and exploitation plan of results

The midterm meeting were organized by prime partner (TUD) and Partner (CEA LIST) with the help of the Bavarian Laser Zentrum (BLZ) which aims to encourage the contact between users, researchers and developers and to provide a discussion forum for current developments in the field of applied laser technology.

Many presentations were done by SUBTUNE partners and several guests. A questionnaire fulfilled by attendees provides a lot of information to the SUBTUNE consortium about market requirements and expected performances.

Moreover, a small exhibition were organized by partners (Table-Top) to present technologies. SUBTUNE Web site: our window opened onto the world The public SUBTUNE website runs since the third project month (June 2009). It has been set up as www.subtune.org which will remain active until at least 2014.

Number of connections remains important with time, proving the interest of this technology.Up to now our public website was visited 38507 times.

SUBTUNE Web site: our window to the world

The public Subutne website runs since the third project month (June 2009). It has been set up as www.subtune.org which will remain active until at least 2014. Number of connexions remains important with time, proving the interest of this technology. Up to March 2012 our public website was visited 38507 times.

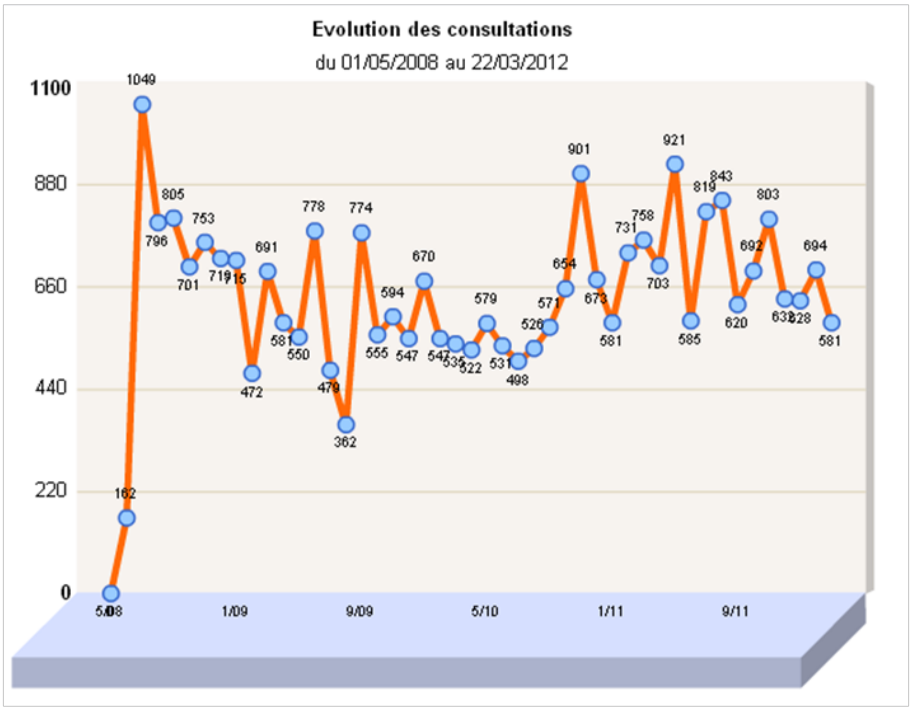


Figure 38: Number of visits of the SUBTUNE website

4.5 Exploitation

4.5.1 New planned projects

- **VERTILAS** and **TUD** are organizing a project together with partners from communication industries to investigate the benefits of the tunable VCSELS and tunable photodiodes for applications in the frame of "access networks" and "optical interconnects". The main idea of this project will be the demonstration of future intelligent networks using e.g. frequency wavelength routing. In addition, it is planned to transfer the technology of surface micromachining long wavelength VCSELs (1.55 μm) from TUD to VERTILAS. After finishing this process, VERTILAS will therefore be able to fabricate tunable VCSELs including half VCSELs and membranes entirely under its own responsibility. The aim of these activities is to provide a larger number of devices suitable to be used for example in gas sensing and communication systems. For FBG measurement system integration a fiber pigtail is required.

- In the framework of a large German research program (LOEWE-Zentrum) **TUD** applied for a project to investigate the applicability of tunable VCSELs in intelligent all optical networks.

- **TUD** applied in another German research program (LOEWE-Schwerpunkt) for a project to develop new widely tunable CW-THz sources based on tunable VCSELs.

- **Leister** and **TUD** will continue their research activities on the field of gas sensing using tunable VCSEL operating around 2000 nm. For that, the packaging will be further improved leading to a larger yield.

- Lawrence Livermore national Laboratories and **TUD** are planning the investigation of SUBTUNE tunable VCSELs for intra cavity gas sensing.
- Recently, another group at **TUD** showed very high interest in 850 nm tunable VCSEL. They are developing tunable solid state lasers (Ti:Saphire) and are interested in using tunable VCSEL as seeding source.
- **TUD** already got 1.5 μm pin diode wavers from partner **TYNDALL** which are suitable to produce tunable detectors for example for future communication networks using the surface micromachining technology developed in the SUBTUNE project. These activities will be performed in close cooperation with **TYNDALL**, when **TUD** have got the available man power resources.
- To understand the physics of the polarization and dynamic behavior of VCSELs under strong optical feedback **TUD** is planning to fabricate a non tunable VCSEL with a tunable integrated external mirror which will provide strong external feedback and where the phase condition can be adjusted to different working points.
- Enhance the SMM-VCSEL-Concept to a MIMS-VCSEL-Concept: the now developed Surface-Micro-Machining VCSELs are divided into two steps, the half-VCSEL growth and fabrication and the evaporation and processing of the dielectric membrane. **TUM** want to combine these two steps and create a new fully monolithically integrated tunable VCSEL structure. The concept of this so called Monolithically-Integrated-MEMS VCSEL has already been presented on the IPRM 2011 and the iNOW 2011 Conferences. For the realization it is planned to exchange the top DBR with a new so called High-Contrast-Grating (HCG). To develop this technology **TUM** is going to start cooperation with the group of Connie Chang-Hasnain (University of Berkley, CA), which is one of the world leading groups in this field.
- Increase of the laser wavelength: Many important industrial gases like H2S, NH3, CO2 and N2O have strong absorption lines beyond 2 μm. To realize single mode laser operation between 2-3 μm, which would cover this important molecular fingerprint region, GaSb-based VCSEL devices are needed. Since **TUM** is world leading in GaSb-based VCSEL technology, therefore **TUM** is planning to combine the developed membrane with such VCSEL instead of only InP-based lasers. This would be a big advantage especially for gas sensing applications.
- **TUM** is planning to transfer the half-VCSEL technology to Vertilas (partner 5 of Subtune). This enables the cooperation between **TUD** (partner 1 of Subtune) and Vertilas, which would provide a larger amount and optimized layout of tunable VCSELs.
- **Tyndall** people claim to be very excited about the possibilities associated with the Subtune technology. They believe that there are great possibilities using these devices especially in long reach PON. Wafer scale integration of the membranes is one breakthrough. Stable and reliable packaging (fibre coupling) and the reliability of the components needs to be. These points could be the basis of a new project.
- **CEA LIST** claims the same thing about packaging and pigtailing concerning for the FBG-based sensing sector.
- **Chalmers** activity on tunable VCSELs is part of the newly founded Fiber Optic Communications Research Centre (FORCE), which combines all research activities at Chalmers related to optical communications and stimulates internal collaborations of the different groups. FORCE covers all aspects of optical communications from signal theory to components and experimental systems. http://www.chalmers.se/mc2/force-en/projects/short-reach-links/tunable-high-speed

- At the same time **Chalmers** is looking into possibilities to form a consortium that can address new EU calls, where technologies developed within Subtune may play an important role. Also see the paragraph devoted to the ”life after SUBTUNE”, below.

4.5.2 Jobs

VERTILAS claims to be interested in the future by a production of 1.55 m tunable VCSEL. In such case jobs will be created. So far, the investigations within Subtune have been carried out with existing personnel. With a successful commercialization of tunable VCSELs, however, VERTILAS expects the creation of new jobs in the production, qualification and related R&D fields.

At LEISTER there are 2-3 potential positions to be created in 2014.

4.5.3 Special Exploitation plans of industrial partners or Institutes more marketing oriented Roadmaps

Exploitation plan of Leister The SME Leister, formerly IRM, is currently preparing its entry in the market of low-cost laser-based gas sensors for such small molecule gases as O2 , CO2, H2O, NH3, CH4 with targeted initial quantities of several hundreds to a few thousands units per year using near-IR VCSELs. Leister is currently negotiating sales contracts with customers having a large market share in their field. The company is working on different tasks such as optical design optimization and calibration automation to achieve the target objectives in terms of sensor simplicity and also cost. For such purpose, Leister also works in strong interaction with laser suppliers in order to improve/simplify such aspects as the test and packaging of the devices for cost optimization. With this approach, it plans to pioneer the commercialization of low-cost gas sensors for large volume markets, since laser-based sensors have been confined to-date to application specific analyzers and industrial monitors with much reduced volumes and costs orders of magnitude higher.

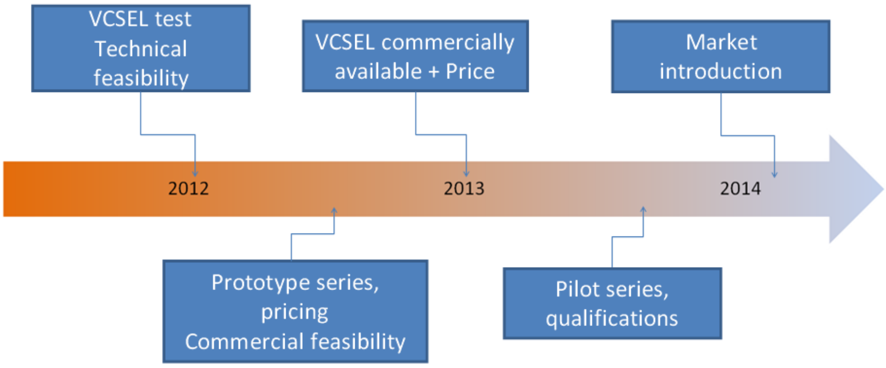


Figure 39: Leister roadmap for Subtunes VCSELs devoted to ”gas sensing”

Exploitation plan of Chalmers Chalmers Roadmap for short wavelength communications The Photonics Lab at Chalmers University of Technology designed and successfully fabricated Ga-As based half-VCSELs in order to enable the development of tunable, single transverse polarization mode VCSELs in the short wavelength (750-1000 nm) range. This activity involved modeling for design and analysis, as well as the intensive use of clean room facilities for VCSELs manufacturing. Based on these results, Chalmers has intend to go further, and now claims to applied these new tunable lasers for data transmissions, as described on the technological road map below.

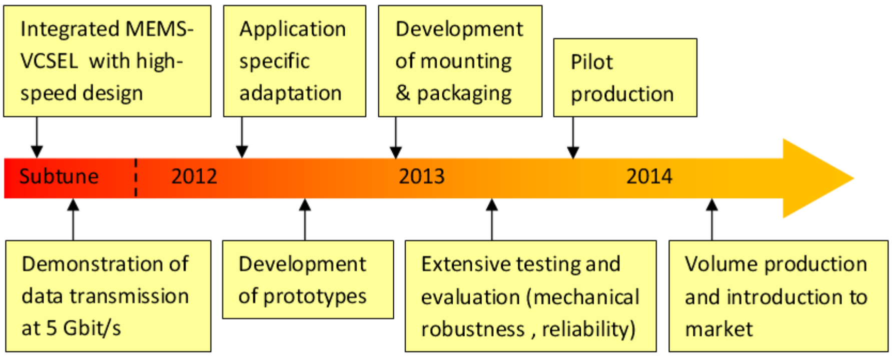


Figure 40: Chalmers roadmap for Subtunes VCSELs devoted to Short wavelength telecommunications

Exploitation plan of CEA LIST CEA LIST FBG-based sensing roadmap for Tunable VCSEL FBG-based measurement system For long wavelength tunable VCSELs (1.55 μm) to use in FBG demultiplexing instrument, the situation is as follows: CEA, right now is not able to really promote the tunable VCSEL technology to industrial end users, as the Institute cannot: integrate the 1.55 m tunable Subtune laser, as today's laser specifications are not yet in agreement with end-user requirements, push on the market any FBG measurement systems based on tunable VCSEL, as reliability (very important on field) of such lasers, is not yet proven, sell or transfer FBG measurement systems technology to a manufacturer as it will cannot be able to purchase such tunable VCSELs today.

Nevertheless, the CEA LIST remains fully confident that tunable VCSEL approach is attractive for OEM & integrated solutions. But, 3 years ago, the Institute must confess he have underestimated the time need for this tunable laser development, from an industrial point-of-view. Thats why the CEA LIST road map (see below) starts at the time such tunable VCSEL, fully packaged and pigtailed and reliable enough, will be available from a commercial point of view, in order to be integrated in industrial measurement systems. From our point of view, such improvements could require at least 3 extra years.

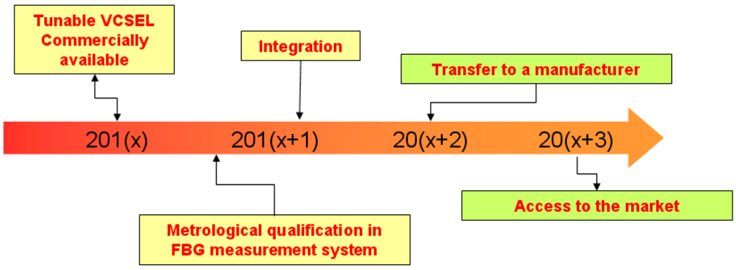


Figure 41: CEA LIST roadmap for applicationm of 1.5 μm VCSELs devoted to fiber Bragg grating sensing

From these road maps, we may understand that "integrators" partners anticipate a 3-4 years delay before the tunable VCSEL technology developed within the Subtune project reach the market.

Manufacturing of Tunable VCSEL: Vertilas orientations & Roadmap For Vertilas, the scope of Subtune project is in distinct relationship to its current product portfolio as well as the future R&D

and commercial strategy of the company. Based on its patented buried tunnel junction (BTJ) technology which was initially developed at the Walter Schottky Institute (TUM) as one of the main collaboration partners of Subtune, Vertilas currently develops, produces and markets BTJ-VCSELs based on InP. The InP-based technology can access the wavelength range up to 2.3 μm.

While applications with fixed or moderately tunable VCSELs in the near IR range up to 2.3m for optical communications and sensing have become a main pillar, Vertilas also faces customer interest in VCSELs with wide tenability of the order of several tens of nanometer. For example, such lasers could substitute multiple fixed wavelength devices and contribute a substantial cost advantage for customers.

Together with its relationships to many worldwide customers in the field of both optical sensing and communications, the extension of this product portfolio with tunable lasers could significantly increase the companys added value and strengthen its position as a leading supplier of long-wavelength VCSELs. Accordingly, the outcomes of the Subtune project are of significantly high interest.

In this context, Vertilas is in close relationship particularly with the partners for device fabrication. As a leading supplier of long-wavelength VCSELs and with its experience in BTJ-VCSEL technology, Vertilas is the predestined partner to adopt the technology of tunable VCSELs.

Furthermore, the tuning technique could open up a versatile way to substantially increase the product portfolio even at extended wavelengths since the surface micromachining concept is independent from the material base for the VCSELs. Thus, it could be also applied for e.g. ultra-long wavelength VCSELs based on GaSb for wavelengths even beyond 3 μm.

Besides the potential decision for a market entry dependent on commercial market considerations, a mandatory precondition is set by the proof of an application compliant device performance. The scientific results of SUBTUNE clearly indicate the potential of the technology to serve as a platform for these new types of long-wavelength VCSELs. This includes fiber coupled output powers well beyond 1mW, spectral purity with at least 30 dB side mode suppression and tuning ranges around 100nm. Naturally, ongoing research efforts are needed particularly to demonstrate the long-term reliability of these new VCSELs. In addition, technological improvements such as polarization control still have to be implemented.

Up to the Subtune project ending, little is known on the cost issues such as yield numbers in an industrial production environment. Optimization of production yields is evidently not part of the project tasks but would be pursued by the future chip manufacturer. Based on the experience of fixed wavelength devices, a competitive and reasonable production yield should be at least 50 % after passing the entire production chain. With this precondition, widely tunable VCSELs would compete well against existing edge emittinglasers or even appear as preferred light source for many applications.

The principal workflow for transferring tunable VCSELs into market is depicted in the figure below.

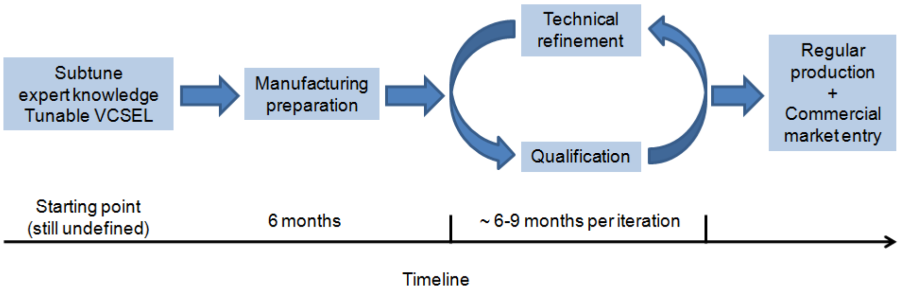


Figure 42: Vertilas roadmap for Subtunes tunable VCSELs manufacturing

From such road map, we understand that Vertilas anticipate roughly 1.5 year delay before the tunable VCSEL lasers developed within the Subtune project reach the market.

Extra comment: In the framework of SUBTUNE, VERTILAS has not filed any patents so far. The company continuously communicates the results from SUBTUNE partners during its participations on industrial exhibitions.

Summary results of project's outcomes	**Number**	
Which is the 'Breakthrough' or 'real' innovation achieved in the considered period	N/A	The development of a technology suitable for on wafer mass production of tunable VCSELs as well for short as for long wavelength tunable VCSELS World record continuous tuning range of 102 nm with an output power larger than 2 mW over the whole tuning range using this technology For a non tuneable VCSEL at 1.5 μm we achieved world record single mode output power of 6.7 mW and a 3 dB modulation bandwidth larger than 10 GHz. Even at 80^oC an output power of more than 2 mW was achieved. We succeeded to develop a tunable VCSEL with an continuous tuning range from 1920 nm up to 1970 nm with an output power in the range of 0.4-1.0 mW suitable for gas sensing systems
Scientific or technical publications on reviewed journals and conferences	56	
Scientific or technical publications on non-reviewed journals and conferences	20	
Invited papers published in scientific or technical journal or conference.	4	
Patents filed and pending	0	When and in which country(ies): Brief explanation of the field covered by the patent:
Patents awarded	0	When and in which country(ies): Brief explanation of the field covered by the patent* (if different from above):
Patents sold	0	When and in which country(ies): Brief explanation of the field covered by the patent* (if different from above):
Creation of start-up	No	If YES, details: - date of creation: - company name - subject of activity: - location: - headcount: - turnover: - profitable : yes / no / when expected
Creation of new department of research (ie: organisational change)	No	Name of department:
Collaboration/ partnership with industry not a member of the consortium	Yes	Which partner :TUD Which company : What kind of collaboration ?Packaging
Active participation to Conferences		
Number of PhD students hired for project's completion	17	In what field :Development of InP & GaAs tunable VCSELs; gas sensing; FBG sensing
Media appearances and general publications (articles, press releases, etc.)	2	

5 Summary Tables

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publi-sher	Place of publica-tion	Year of public-cation	Relevant pages	Permanent identifiers[1] (if available)	Is/Will open access[2] provided to this publication?
1	*Surface micromachined tunable 1.55 µm-VCSEL with 102 nm continuous single-mode tuning*	*C. Gierl, T. Gründl, P. Debernardi, K. Zogal, C. Grasse, H. A. Davani, G. Böhm, S. Jatta, F. Küppers, P. Meissner, M-C. Amann*	*Optics Express*	*Issue 18*	*OSA*		*2011*	*17336-17343*	*http://www.opticsinfobase.org/oe/abstract.cfm?uri=oe-19-18-17336*	*Yes*
2	*Integrated MEMS-Tunable VCSELs Using a Self-Aligned Reflow Process*	*B. Kögel, P. Debernardi, P. Westbergh, J. S. Gustavsson, Å. Haglund, E. Haglund, J. Bengtsson, and A. Larsson*	*IEEE J. Quantum Electron.*	*Issue 2*	*IEEE*		*2012*	*144-152*		*No*
3	*Modal Properties of Long-Wavelength Tunable MEMS-VCSELs With Curved Mirrors: Comparison of Experiment and Modelling*	*P. Debernardi, B. Kögel, K. Zogal, P. Meissner, M.Maute, M. Ortsiefer, G. Böhm, M.-C. Amann:*	*IEEE J. Quantum Electron.*	*Issue 4*	*IEEE*		*2008*	*391-399*		*No*
4	*Surface micromachined MEMS-tunable VCSELs with wide and fast wavelength tuning*	*C. Gierl, T. Gründl, K. Zogal, H.A. Davani, C. Grasse, G. Böhm, F. Küppers, P. Meissner, M-C. Amann*	*Electronic Letters*	*Issue 22*	*IEE*		*2011*	*1242-1243*		*No*
5	*Integrated MEMS-tunable VCSELs with high modulation bandwidth*	*B. Kögel, P. Westbergh, Å. Haglund, J. S. Gustavsson and A. Larsson*	*Electronic Letters*	*Issue 13*	*IEE*		*2011*	*764 – 765*		*No*

---

[1] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[2] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

6	*1550-nm High-Speed Short-Cavity VCSEL*	*M. Müller, W. Hofmann, T. Gründl, M. Horn, P. Wolf, R. D. Nagel, E. Roenneberg, G. Böhm, D. Bimberg, M.-C. Amann*	*Journal Selected Topics Quantum Electronics*	*Issue 5*	*IEEE*		*2011*	*1158 - 1166*		*No*
7	*Bulk-Micromachined VCSEL At 1.55 µm With 76-nm Single-Mode Continuous Tuning Range*	*S. Jatta, B. Kögel, M. Maute, K. Zogal, F. Riemenschneider, G. Böhm, M.-C. Amann, P. Meissner*	*IEEE Photonics Technology Letters*	*Issue 24*	*IEEE*		*2009*	*1822-1824*		*No*
8	*Depositon of Dielectric Films with Inductively Coupled Plasma-CVD in Dependence on Pressure and Two RF-Power-Sources*	*S. Jatta, K. Haberle , A. Klein, R. Schafranek, B. Kögel, P. Meissner*	*Plasma Processes and Polymers*	*Issue 1*	*Wiley*		*2009*	*S582–S587*		*No*
9	*Empirical modeling of the refractive index for (AlGaIn)As lattice matched to InP*	*C. Grasse, G Böhm, M Müller, T Gründl, R Meyer, M.-C. Amann*	*IOP Publishing Semicond. Sci. Technol*	*Issue 9*			*2010*	*1-4*		*No*
10	*Spectral and modulation properties of a largely tunable MEMS-VCSEL in view of gas phase spectroscopy applications*	*S. Schilt, · K. Zogal, · B. Kögel, · P. Meissner, · M. Maute, R. Protasio, M.-C. Amann*	*Special issue of Appl. Phys. B*	*Issue 2*			*2010*	*321-329*		*No*
11	*Experimental comparison of piezoresistive MEMS and fiber Bragg grating strain sensors*	*J. Rausch, P. Heinickel, R. Werthschuetzky, B. Kögel, K. Zogal, P. Meissner,*	*Sensors*	*Oct.*	*IEEE*		*2009*	*1329-1333*		*No*
12	*Up to 3µm light emission on InP substrate using GaInAs/GaAsSb type-II quantum wells*	*S. Sprengel, C. Grasse, K. Vizbaras, T. Gründl, M-C. Amann*	*Appl. Phys. Lett.*	*Issue 22*	*OSA*		*2011*	*221109*		*No*
13	*Realization of tunable optical components with ICP-CVD Frequenz 3/4-2008.*	*S. Jatta, K. Zogal, K. Kögel, K. Haberle, C. Sydlo*	*Frequenz*				*2008*	*96-97*		*No*
14	*AM and RIN of a Long-Wavelength Tunable MEMS VCSEL*	*K. Zogal, B. Kögel, P. Meissner*	*Frequenz*	*Issue 3-4*			*2008*	*93-95*		*No*
15	*10 Gb/s transmission over 50 km of SMF using MEMS tuneable VCSEL*	*A. Daly, C. Gierl, T. Gründl, C. Grasse, K. Zogal, D. Carey, P. Townsend, M. -C. Amann, P. Meissner and B. Corbett*	*Electronics Letters*	*March 29*	*IET*		*2012*			

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[3]	Main leader	Title	Date	Place	Type of audience[4]	Size of audience	Countries addressed
1	*Invited Presentation at Conference*	*T. Gründl, M. Müller, K. Vizbaras, C. Grasse, M.-C. Amann*	*"Present status of long-wavelength VCSELs: device structures, performance and applications" at IEEE Photonics Conference*	*Sept. 23th - 27th 2012*	*Burlingame, California USA*	*SC*	*600*	*World*
2	*Presentation at Conference*	*C. Grasse, M. Müller, T. Gründl, G. Böhm, E. Roenneberg, P. Wiecha, M. Ortsiefer, R. Meyer, M-C. Amann*	*"AlGaInAsPSb-based High-Speed Short-Cavity VCSEL with single-mode Emission at 1.3µm grown by MOVPE on InP substrate" at 16th International Conference on Metal Organic Vapor Phase Epitaxy (ICMOVPE)*	*May, 20th-25th 2012*	*Busan, South Korea*	*SC, Industry*		*World*
3	*Presentation at Conference*	*C. Grasse, T. Gründl, S. Sprengel, P. Wiecha, K. Vizbaras, R. Meyer, M-C. Amann*	*"GaInAs/GaAsSb-based type-II Micro-Cavity LED with 2-3µm light emission grown on InP substrate" at 16th International Conference on Metal Organic Vapor Phase Epitaxy ICMOVPE*	*May, 20th-25th 2012*	*Busan, South Korea*	*SC*		*World*
4	*Presentation at Conference*	*K. Zogal, T. Gründl, C.Gierl, C. Grasse, H. Davani, G. Böhm, P. Meissner, F. Küppers, M.-C. Amann*	*Singlemode 50nm Tunable Surface Micro-Machined MEMS-VCSEL Operating at 1.95µm, CLEO 2012, San Jose, California, USA, May 8,*	*May 8th 2012*	*San Jose USA*	*SC, Industry*	*500*	*World*
5	*Presentation at Conference*	*C. Gierl, T. Gründl, K. Zogal, C. Grasse, H.A. Davani, G. Böhm, F. Kueppers, P. Meissner, M.-C. Amann*	*"Linewidth of surface micro-machined MEMS tunable VCSELs at 1.5µm" at CLEO*	*May 8th 2012*	*San Jose USA*	*SC, , Industry*	*400*	*World*
6	*Presentation at Conference*	*M. Ortsiefer, J. Rosskopf, C. Neumeyr, T. Gründl, C. Grasse, J. Chen, A. Hangauer, R. Strzoda, C. Gierl, P. Meissner, F. Küppers, M.-C. Amann,*	*"Long-wavelength VCSELs for sensing applications" at SPIE Photonics West*	*January 21st -26th 2012*	*San Francisco, USA*	*SC, Industry*	*600*	*World*
7	*Presentation at Conference*	*K. Zogal, T. Gründl, H. Davani, C. Gierl, P. Meissner, F. Kueppers, M.-C. Amann*	*„1.55-µm high-speed MEMS-tunable VCSEL" at SPIE Photonics West*	*January 21st -26th 2012*	*San Francisco, USA*	*SC, Industry*	*600*	*World*
8	*Presentation at Conference*	*H. A. Davani, B. Kögel ,P. Debernardi, C. Grasse, C. Gierl, K. Zogal, Å. Haglund, J. Gustavsson, P. Westbergh, T. Gründl, P. Komissinskiy, T.Bitsch, L. Alff, F. Küppers, A. Larsson, M. C. Amann, P.*	***"**Polarization Investigation of a Tunable High Speed Short-Wavelength Bulk-Micromachined MEMS-VCSEL" at SPIE Photonics West*	*January 21st -26th 2012*	*San Francisco, USA*	*SC, Industry*	*600*	*World*

---

[3] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[4] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias ('multiple choices' is possible.

		Meissner						
9	*Presentation at Conference*	*C. Gierl, T. Gründl, P. Debernardi, K. Zogal, H. A. Davani, C. Grasse, G. Böhm, F. Küppers, P. Meissner, M.-C. Amann*	*"Surface micromachined MEMS tunable VCSEL at 1550 nm with >60 nm single mode tuning" at SPIE Photonics West*	*January 21st -26th 2012*	*San Francisco, USA*	*SC, Industry*	*600*	*world*
10	*Presentation at Conference*	*B. Kögel, P. Debernardi, P. Westbergh, J. S. Gustavsson, Å. Haglund, E. Haglund, J. Bengtsson, A. Larsson*	*"Integrated MEMS-tunable VCSELs for reconfigurable optical interconnects" at SPIE Photonics West*	*January 21st -26th 2012*	*San Francisco, USA*	*SC, Industry*	*600*	*world*
11	*Invited Presentation at Conference*	*A. Larsson, J. Gustavsson, Å. Haglund, B. Kögel, P. Westbergh, E. Haglund*	*"High speed tunable and fixed wavelength VCSELs for short reach optical links and interconnects" at SPIE Photonics West*	*January 21st -26th 2012*	*San Francisco, USA*	*SC, Industry*	*600*	*world*
12	*Presentation at Conference*	C. Grasse, S. Sprengel, K. Vizbaras, T. Gründl, P. Wiecha, R. Meyer, M.-C. Amann	*"GaInAs/GaAsSb type-II quantum wells for up to 2.8 µm light emission on InP substrate"* at 26. DGKK-Workshop,	December, 8th -9th 2011	Stuttgart, Germany	*SC*		*world*
13	*Presentation at Conference*	T. Gründl, C. Gierl, C. Grasse, K. Zogal, G. Böhm, R. Meyer, M. C. Amann, P. Meissner,	*„First 102 nm Ultra-Widely Tunable MEMS VCSEL Based on InP"* at IEEE Photonics 2011 Conference (IPC11) - (formerly Photonics Society Annual Meeting), paper ThDD1,	October, 2011	Arlington, Virginia (USA)	*SC*		*world*
14	*Presentation at Conference*	A. Daly, A. M Clarke,T. Grundl, M-.C. Amann, B. Corbett, and P. D. Townsend	*10 GBIT/S DIRECTLY MODULATED LONG-WAVELEGNTH VCSELS FOR UPSTREAM HYBRID TDMA/WDM PON*	Oct 2011	Dublin Ireland	*SC*	*200*	*National*
15	*Presentation at Conference*	T. Gründl, C. Grasse, M. Müller, G. Böhm, R. Meyer, K. Zogal, C. Gierl, S. Jatta, P. Meissner, M. C. Amann	*"Widely Tunable 1.55 µm High-Speed, Short-Cavity MEMS VCSELs"* at European Semiconductor Laser Workshop (ESLW)	September. 23rd -24th 2011	Lausanne Switzerland			
16	*Presentation at Conference*	H. Davani, C. Grasse, B. Kögel, C. Gierl, K. Zogal, T. Gründl, Petter Westbergh, S. Jatta, G. Böhm, P. Meissner, A. Larsson, M.-C. Amann	"Widely Electro Thermal Tunable Bulk-Micromachined MEMS-VCSEL Operating Near 850 nm" at IQEC/CLEO 2011 Pacific Rim Conference	28th August-1st Sept. 2011,	Sydney Australia	*SC*		*world*
17	*Presentation at Conference*	T. Gründl, C. Gierl, K. Zogal, C. Grasse, M. Müller, G. Böhm, R. Meyer, M.-C. Amann, P. Meissner	"Concepts and Realization of Widely Tunable InP VCSELs" at International Nano-Optoelectronics Workshop (iNow)	July 24th - August 6th 2011	St. Petersburg, Russia & Würzburg Germany	*SC*		*world*
17	*Presentation at Conference*	*C. Grasse, T. Gründl, M. Müller, R. Meyer, M.-C. Amann*	"GaAsSb:C / GaInAs:Si tunnel junctions with AlGaInAsSb:C grading for InP-based high-speed VCSELs" at European Workshop on Metalorganic Vapor Phase Epitaxy (EWMOVPE XIV)	June 5th -8th 2011	Wroclaw, Poland	*SC*		*world*
18	*Presentation at Conference*	K. Zogal, C. Gierl, H. Davani, C. Grasse, M. Maute, P. Meissner, M.-C. Amann	"Tuning dynamics of a > 70 nm continuously tunable MEMS-VCSEL with a hybrid curved mirror", CLEO Europe	*May 22nd - 26th 2011*	*Munich Germany*	*SC Industry*		*world*
19	*Presentation at Conference*	T. Gründl, D. Pierluigi, M. Ortsiefer, C. Grasse, M.-C. Amann	"Novel concept for a Monolithically Integrated MEMS VCSEL" at 23rd Intern. Conf. on Indium Phosphide and Related Materials – IPRM	*May 22nd - 26th 2011*	*Berlin Germany*	*SC*		*world*
20	*Presentation at workshop*	K. Zogal	, "High Speed Modulation of a 1.55-µm MEMS-Tunable VCSEL", VCSEL Day 2011	*May 12th 2011*	*Toulouse France*	*SC*	*50*	*Europe*

21	*Presentation at workshop*	M. Ortsiefer	“Recent Progress of InP-based Long-Wavelength VCSELs for Communications and Sensing Applications”, VCSEL Day 2011	*May 12th 2011*	*Toulouse France*	*SC*	*50*	*Europe*
22	*Presentation at workshop*	P. Meissner	“Strategy for the development of tunable VCSELs”, VCSEL, Day 2011	*May 12th 2011*	*Toulouse France*	*SC*	*50*	*Europe*
23	*Presentation at workshop*	B. Kögel, P. Westbergh, Å. Haglund, J. Gustavsson, A. Larsson, P. Debernardi	*“Integrated MEMS-Tunable VCSELs Using a Self-Aligned Reflow Process”, VCSEL Day*	*May 12th 2011*	*Toulouse France*	*SC*	*50*	*Europe*
24	*Presentation at workshop*	C. Gierl	“102 nm Continuous Single-Mode Tuning with a Surface Micro-Machined tunable VCSEL*”, VCSEL Day*	*May 12th 2011*	*Toulouse France*	*SC*	*50*	*Europe*
25	*Presentation at workshop*	P. Debernardi	“Collimating VCSEL light by integrated microlenses: comparison of experiment and modeling*”, VCSEL Day*	*May 12th 2011*	*Toulouse France*	*SC*	*50*	*Europe*
26	*Presentation at workshop*	B. Corbett	“Voltage spectroscopy of long wavelength VCSELs under optical injection*”, VCSEL Day*	*May 12th 2011*	*Toulouse France*	*SC*	*50*	*Europe*
27	*Presentation at Conference*	B. Kögel, P. Debernardi, P. Westbergh, Å. Haglund, J. Gustavsson, J. Bengtsson, E. Haglund, A. Larsson:	*“Singlemode tunable VCSELs with integrated MEMS technology” at European Conference on Laser and Electro-Optics (CLEO/Europe)*	*May 2011*	*Munich Germany*	*SC, Industry*	*500*	*world*
28	*Presentation at Conference*	*C. Gierl, K. Zogal, H. A. Davani, P.Meissner*	*"Electro Thermal and Electro Statical Actuation of a Surface Micromachined Tunable Fabry-Perot Filter" at “, Conference on Lasers and Electro Optics (CLEO)*	*May 1st 2011*	*Baltimore, Maryland, USA*	*SC, Industry*		*world*
29	*Presentation at Conference*	T. Gründl, M. Müller, K. Geiger, C. Grasse, G. Böhm, R. Meyer, M.-C. Amann	„High-Power BCB Encapsulated VCSELs based on InP“ at Conference on Lasers and Electro Optics (CLEO)	*May 1st 2011*	*Baltimore, Maryland, USA*	*SC, Industry*		*world*
30	*Presentation at Conference*	*K. Zogal, T. Gründl, H. A. Davani, C. Gierl, S. Jatta, C. Grasse, M.-C. Amann, P. Meissner*	*" High Speed Modulation of a 1.55-µm MEMS-tunable VCSEL“ at Conference on Lasers and Electro Optics (CLEO)*	*May 1st 2011*	*Baltimore, Maryland, USA*	*SC, Industry*		*world*
31	*Invited Presentation at Conference*	C. Gierl, K. Zogal, S. Jatta, H. A. Davani, F. Küppers, P. Meissner, T. Gründl, C. Grasse, M.-C. Amann, A. Daly, B. C., B. Kögel, A. Haglund, J. Gustavsson, P. Westbergh, A. Larsson, P. Debernardi, M. Ortsiefer	*“Tuneable VCSEL aiming for the application in interconnects and short haul systems”* at SPIE Photonics West	*January* 26th -28th 2011	San Francisco, CA, USA	*SC, Industry*		*world*
32	*Presentation at Conference*	*C. Grasse, T. Gründl, T. Hager, M. Törpe, R. Meyer*	*"Growth and Characterisation of GaAsSb:C/GaInAs:Si Tunnel Junctions for InP-based Long-Wavelength VCSELs" at 25. DGKK-Workshop, Aachen 2010*	December, 9th-10th 2010	Aachen Germany			
33	*Presentation at Conference*	*M. Müller, T. Gründl, M. Horn, R. Nagel, W. Wiedmeier, E. Rönneberg, G. Böhm, M.-C. Amann*	*„Small-Signal Analysis of High-Temperature Stable 1550nm High-Speed VCSELs" at 6th Joint Symposium on Opto- and Microelectronic Devices and Circuits*	October, 4th-6th 2010	Berlin Gemany	*SC*		*world*
34	*Presentation at Conference*	*H. A. Davani, C. Grasse, B. Kögel, C. Gierl, K. Zogal, S. Jatta, G. Böhm, T. Gründl, P. Meissner, A. Larsson, M.-C. Amann*	*"Widely tunable high-speed bulk-micromachined short-wavelength MEMS-VCSEL"at , Semiconductor Laser Conference (ISLC),*	September 26th -30th 2010	Kyoto Japan	*SC*		*world*
35	*Presentation*	*B. Kögel, A. Abbaszadehbanaeiyan,*	*“Integrated Tunable VCSELs With Simple MEMS*	September	*Kyoto, Japan*			

	at Conference	*P. Westbergh, Å. Haglund, J. Gustavsson, J. Bengtsson, E. Haglund, H. Frederiksen, P. Debernardi, A. Larsson*	*Technology" Semiconductor Laser Conference (ISLC)*	26th -30th 2010				
36	*Presentation at Conference*	*T. Gründl, K. Zogal, M. Müller, R. Nagel, S. Jatta, K. Geiger, C. Grasse, G. Böhm, M. Ortsiefer, Ralf Meyer, P. Meissner, M.-C. Amann*	*"High-Speed and High-Power Vertical-Cavity Surface-Emitting Lasers based on InP suitable for Telecommunication and Gas Sensing" at SPIE Remote Sensing, Security and Defence*	September 20th-23rd 2010	*Toulouse, France*	*SC*		*world*
37	*Presentation at Conference*	*T. Gründl, M. Müller, R. Nagel, K. Geiger, G. Böhm, C.Grasse, M. Ortsiefer, M.-C. Amann*	*"High-Speed High-Power VCSELs based on InP" at International Nano-Optoelectronics Workshop (iNow) 2010,*	August 1st - 15th 2010	*Peking & Changchun, China*	*SC*		*Europe*
38	*Presentation at workshop*	*P. Meissner*	*"The SUBTUNE project: Widely tuneable VCSELs, ", VCSEL Day*	May 7th 2010	Turino Italy	*SC*	*50*	*EU*
39	*Presentation at workshop*	*K. Zogal*	*"Different concepts for MEMS tuneable VCSEs ", VCSEL Day*	May 7th 2010	Turino Italy	*SC*	*50*	*EU*
40	*Presentation at workshop*	*B. Kögel*	*"Short-wavelength tunable VCSELs", VCSEL Day*	May 7th 2010	Turino Italy	*SC*	*50*	*EU*
41	*Presentation at workshop*	*A .Haglund*	*"High-speed 850 nm VCSELs", VCSEL Day*	May 7th 2010	Turino Italy	*SC*	*50*	*EU*
42	*Presentation at workshop*	*T. Gründl*	*"BCB encapsulated VCSEL based on InP suitable for MEMS Technology", VCSEL Day*	May 7th 2010	Turino Italy	*SC*	*50*	*EU*
43	*Presentation at workshop*	*B. Corbett*	*"Excitation and manipulation of surface plasmons using VCSELs", VCSEL Day*	May 7th 2010	Turino Italy	*SC*	*50*	*EU*
44	*Mid-term Workshop organized by SUBTUNE*	*All partners of SUBTUNE*	*Tunable Cavity Surface Emitting Lasers*	*February 26th 2010*	*Nuremberg Germany*	*Industry SC*	*34*	*Europe*
45	*Presentation at Conference*	*A. J. Daly, B. J. Roycroft, F. H. Peters, M. Ortsiefer, and B. Corbett*	*"Dynamics of 1.55 µm buried tunnel junction VCSELs under optical injection around threshold" at SPIE Photonics West*	*January 2010*	*San Francisco, CA, USA*	*SC, Industry*		*world*
46	*Invited Presentation at Conference*	Peter Meissner, Benjamin Kögel, Karolina Zogal, Sandro Jatta, Christian Gierl, Christian Grasse, Tobias Gründl, Markus-Christian Amann, Petter Westbergh, Johan Gustavsson, Åsa Haglund, Anders Larson, Markus Ortsiefer, Pierluigi Debernardi:	"Widely Tuneable Micromachined VCSELs (New Results)" at *10th Chitose Int. forum on Photonics Science & Technology,* Chitose, Japan.	November 13th -14th 2009	Chitose Japan	*SC*	*100*	*world*
47	*Presentation at Conference*	Benjamin Kögel, Petter Westbergh, Johan Gustavsson, Åsa Haglund, and Anders Larsson	"Short-wavelength tunable VCSELs" at European Semiconductor Laser Workshop (ESLW)	September 26th 2009	Vienna, Austria	*SC*		*world*
48	*Presentation at Conference*	S. Schilt, K. Zogal, B. Kögel, P. Meissner, M. Maute, R. Protasio, M.-C. Amann	"Application of Largely Tunable MEMS-VCSEL to Gas Phase Derivative Spectroscopy" at *7th International Conf. on Tunable Diode Laser Spectroscopy (TDLS)*	July 13th-17th 2009	Zermatt, Switzerland,	*SC*		*world*

49	*Presentation at Conference*	C. Gierl, G. D. Cole, B. Kögel, S. Jatta, K. Zogal, H. Davani, P. Meissner:	"Mechanical properties of a movable micro-mirror membrane for electro-statically tunable optical filters and vertical-cavity surface-emitting lasers" at *European Conference on Laser and Electro-Optics (CLEO/Europe)*	June14th - 19th 2009	Munich, Germany,	*SC*		*world*
50	*Poster Presentation at Conference*	C. Grasse, M. Müller, G. Böhm, M. Ortsiefer, and M.-C. Amann (European Workshop on Metalorganic Vapour Phase Epitaxy), Poster presentation. Extended Abstract in the booklet, pp. 73-74	"Planarization of overgrown tunnel junctions for InP-based VCSEL by MOVPE", 13th EWMOVPE	June 7th- 10th 2009	Ulm Germany	*SC*		*world*
51	*Presentation at Conference*	Nicolas Roussel, Guillaume Laffont and Pierre Ferdinand, *Tunable VCSEL for Fiber Bragg Grating measurement, Subtune project*,	A Future in Light Conference, Supélec	March 27th 2009.	Metz France	*SC*		*world*
52	*Presentation at workshop*	P. Meissner	"SUBTUNE: "Introduction and overview ",VCSEL Day	April 24th 2009	Gotheburg Sweden	*SC*	*50*	*EU*
53	*Presentation at workshop*	A. Larsson	"Design and technologies of high speed half-VCSEL based on GaAs",VCSEL Day	April 24th 2009	Gotheburg Sweden	*SC*	*50*	*EU*
54	*Presentation at workshop*	T. Gründl	"Design and technologies of high speed half-VCSEL based on InP",VCSEL Day	April 24th 2009	Gotheburg Sweden		*50*	*EU*
55	*Presentation at workshop*	K. Zogal, H. Davani	"Bulk-micromachined and integrated tunable VCSELs", VCSEL Day	April 24th 2009	Gotheburg Sweden		*50*	*EU*
56	*Presentation at workshop*	P. Debernardi	"Tunable VCSEL design by VELM simulations",VCSEL Day	April 24th 2009	Gotheburg Sweden		*50*	*EU*
57	*Presentation at Conference*	Sandro Jatta, Klaus Haberle , Andreas Klein , Robert Schafranek , Benjamin Kögel , Peter Meissner	"Depositon of Dielectric Films with Inductively Coupled Plasma-CVD in Dependence on Pressure and Two RF-Power-Sources" at *Eleventh International Conference on Plasma Surface Engineering (PSE2008)*	*September 15th-19th 2008*	Garmisch Patenkirchen, Germany	*SC*		*world*
58	*Presentation at Conference*	B. Kögel, K. Zogal, S. Jatta, C. Grasse, M.-C. Amann, G. D. Cole, M. Lackner, M. Schwarzott, F. Winter, P. Meissner	"Micromachined tunable vertical-cavity surface-emitting lasers with narrow linewidth for near infrared gas detection" at *International Symposium on Optomechatronic Technologies (ISOT)*	November 17th-19th 2008	San Diego USA,	*SC*		*world*
59	*Presentation at Conference*	B. Kögel, K. Zogal, S. Jatta, M. Maute, C. Grasse, M.-C. Amann, P. Meissner	"Small Signal Dynamics of an Electrically Pumped Long-Wavelength Tunable VCSEL" at *IEEE International Semiconductor Laser Conference (ISLC);*	September 14th-18th 2008	Sorrento Italy	*SC*		
60	*Presentation at Conference*	S. Jatta, K. Haberle, A. Klein, B. Kögel, H. Halbritter, P. Meissner*,* Paper 10-51, Glasgow	"Bulk-micromachined dielectric tunable optical filter realized with inductively-coupled plasma chemical vapour deposition" at *Europe Optical System Design, SPIE 7010: Advances in Optical Thin Films III*	September 1st-5th 2008	*Glasgow, Scotland*	*SC*		

Section B (Confidential[5] or public: confidential information to be marked clearly)

Part B1

We did not file any patent applications during the project

Part B2

Type of Exploitable Foreground[6]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[7]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
Commercial exploitation of R&D results,	*New surface micro-machining technologies*	*YES*		*Technology*	*Tunable VCSELs for many applications*	*2014 by VERTILAS*	*No*	*Beneficiaries TUD, TUM, Chalmers; VERTILAS*

---

[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[7] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

6 Report on Social Implications

Report on societal implications Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when **Grant Agreement number** is entered.*

Grant Agreement Number:	224259
Title of Project:	Widely Tunable VCSEL using Sub Wavelength Grating
Name and Title of Coordinator:	Prof. Dr.-Ing. Peter Meissner

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	No
2. Please indicate whether your project involved any of the following issues (tick box) :	No
RESEARCH ON HUMANS	
• Did the project involve children?	No
• Did the project involve patients?	No
• Did the project involve persons not able to give consent?	No
• Did the project involve adult healthy volunteers?	No
• Did the project involve Human genetic material?	No
• Did the project involve Human biological samples?	No
• Did the project involve Human data collection?	No
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	No
• Did the project involve Human Foetal Tissue / Cells?	No
• Did the project involve Human Embryonic Stem Cells (hESCs)?	No
• Did the project on human Embryonic Stem Cells involve cells in culture?	No
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	No
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	No
• Did the project involve tracking the location or observation of people?	No
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	No
• Were those animals transgenic small laboratory animals?	No
• Were those animals transgenic farm animals?	No
• Were those animals cloned farm animals?	No
• Were those animals non-human primates?	No
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	**No**
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	**No**
DUAL USE	
• Research having direct military use	No
• Research having the potential for terrorist abuse	

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	**Number of Women**	**Number of Men**
Scientific Coordinator	0	1
Work package leaders	0	7
Experienced researchers (i.e. PhD holders)	0	1
PhD Students	1	17
Other	2	5

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	
Of which, indicate the number of men: 8	8

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?	○ X	Yes No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective				**Very effective**
☐	Design and implement an equal opportunity policy	○	○	○	○	○
☐	Set targets to achieve a gender balance in the workforce	○	○	○	○	○
☐	Organise conferences and workshops on gender	○	○	○	○	○
☐	Actions to improve work-life balance	○	○	○	○	○
○	Other:					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

X No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

X Yes- please specify

○ No

TUD:
- Bachelor thesis on modeling tunable VCSELs
- PhD thesis on tunable VCSELs

TUM
- 3 Master thesises
  (Spectral gain measurements, Design and fabrication of InP-based membranes, growth of GaInAs/GaAsSb tunnel junctions by MOVPE
- 1 Bachelor thesis
  (Modeling and characterization of SWGs)
- 1 Internship
  (Characterization of InP-based buried tunnel junctions)
- 3 Practica for school pupils (Tenth grade, annualy)
- Participation in open days (annualy)

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

○ Yes- please specify

No

○ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

X Main discipline[1]: 2.2

○ Associated discipline[1]:1.2	○	Associated discipline[1]:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*	○ X	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

- ○ No
- ○ Yes- in determining what research should be performed
- ○ Yes - in implementing the research
- ○ Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

- ○ No
- ○ Yes- in framing the research agenda
- ○ Yes - in implementing the research agenda
- ○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- ○ No

13b If Yes, in which fields?

Agriculture
Audiovisual and Media
Budget
Competition
Consumers
Culture
Customs
Development Economic and Monetary Affairs
Education, Training, Youth
Employment and Social Affairs

Energy
Enlargement
Enterprise
Environment
External Relations
External Trade
Fisheries and Maritime Affairs
Food Safety
Foreign and Security Policy
Fraud
Humanitarian aid

Human rights
Information Society
Institutional affairs
Internal Market
Justice, freedom and security
Public Health
Regional Policy
Research and Innovation
Space
Taxation
Transport

---

[1] Insert number from list below (Frascati Manual).

13c If Yes, at which level?

○ Local / regional levels
○ National level
○ European level
○ International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**14**
To how many of these is open access[2] provided?	**2**
How many of these are published in open access journals?	
How many of these are published in open repositories?	
To how many of these is open access not provided?	
Please check all applicable reasons for not providing open access:	**12**
X publisher's licensing agreement would not permit publishing in a repository ☐ no suitable repository available ☐ no suitable open access journal available ☐ no funds available to publish in an open access journal ☐ lack of time and resources ☐ lack of information on open access ☐ other[3]: ……………	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**0**

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**

17. How many spin-off companies were created / are planned as a direct result of the project?	**0**
Indicate the approximate number of additional jobs in these companies:	**0**

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

☐ Increase in employment, or
☐ Safeguard employment, or
☐ Decrease in employment,
X Difficult to estimate / not possible to quantify

☐ In small & medium-sized enterprises
☐ In large companies
☐ None of the above / not relevant to the project

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*

---

[2] Open Access is defined as free of charge access for anyone via Internet.
[3] For instance: classification for security project.

Difficult to estimate / not possible to quantify	X

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes X No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes X No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

- ☐ Press Release
- ☐ Media briefing
- ☐ TV coverage / report
- ☐ Radio coverage / report
- X Brochures /posters / flyers
- ☐ DVD /Film /Multimedia
- X Coverage in specialist press
- X Coverage in general (non-specialist) press
- ☐ Coverage in national press
- ☐ Coverage in international press
- X Website for the general public / internet
- X Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

- ☐ Language of the coordinator
- ☐ Other language(s)
- X English

Question F-10: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES
1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]
1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)
1.3 Chemical sciences (chemistry, other allied subjects)
1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)
1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY
2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)
2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]
2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as

geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. Medical Sciences

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)
3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)
3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. Agricultural sciences

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)
4.2 Veterinary medicine

5. Social sciences

5.1 Psychology
5.2 Economics
5.3 Educational sciences (education and training and other allied subjects)
5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. Humanities

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)
6.2 Languages and literature (ancient and modern)
6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]