1 Publishable summary

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 for 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.

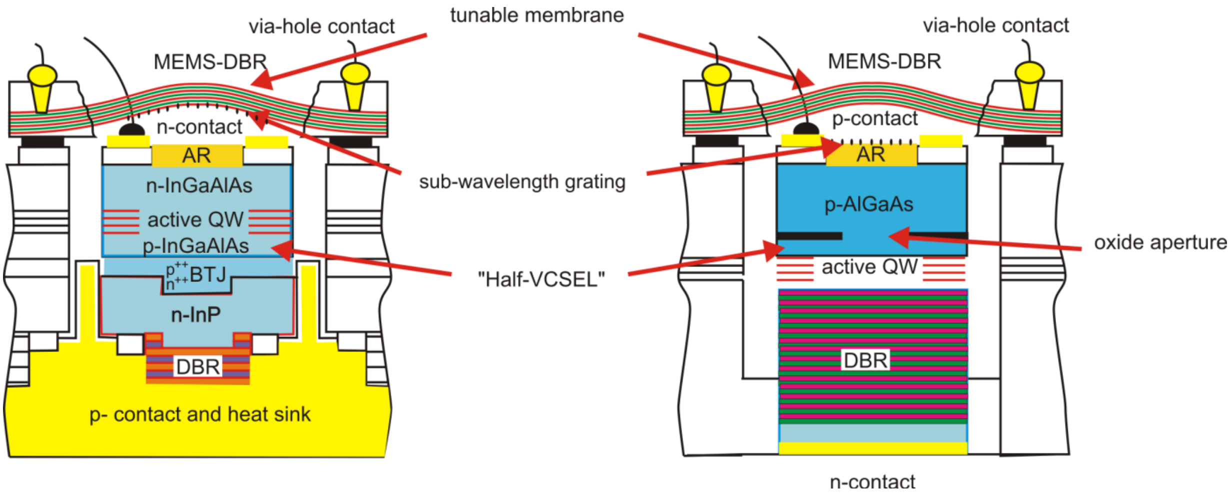

Figure 1: *Structure of a tunable long-wavelength VCSEL with sub wavelength grating for the long (left hand side) and short wavelength (right hand side) region.*

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 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 à 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.

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).

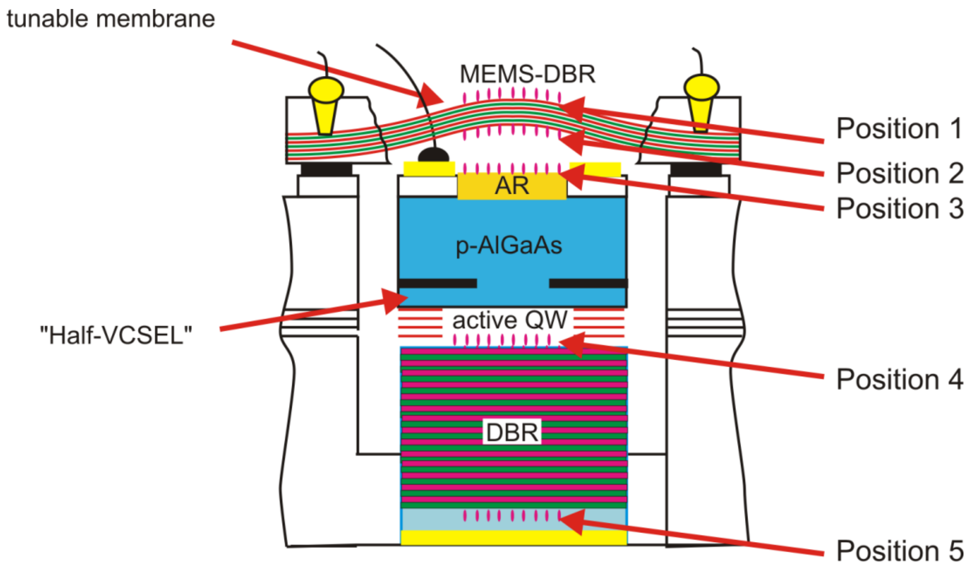

Figure 2: ***Possible positions of the SWGs in our micromechanically tunable VCSELs***

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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 position 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.

SUBTUNE succeeded to develop GaAs based VCSELs as well as InP based tunable VCSELs with excellent and world record properties. But additionally we developed a non tunable VCSEL with World record performance showing an output power of 6.7 mW and a 3 dB modulation bandwidth of 11.2 GHz. This device showed a very low resistance since most of the p-doped material could be exchanged by high conducting n-material due to the 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.

In Figure 3 the schematic cross section of a non tunable typical high speed 1.55 µm half-VCSEL is given. This VCSEL developed by the SUBTUNE project is provided with a dielectric mirror deposited directly on the top of the half VCSEL. This device showed a record single mode output power of 6.4 mW and a modulation bandwidth larger than 10 GHz. This device is suitable for high speed communication systems.

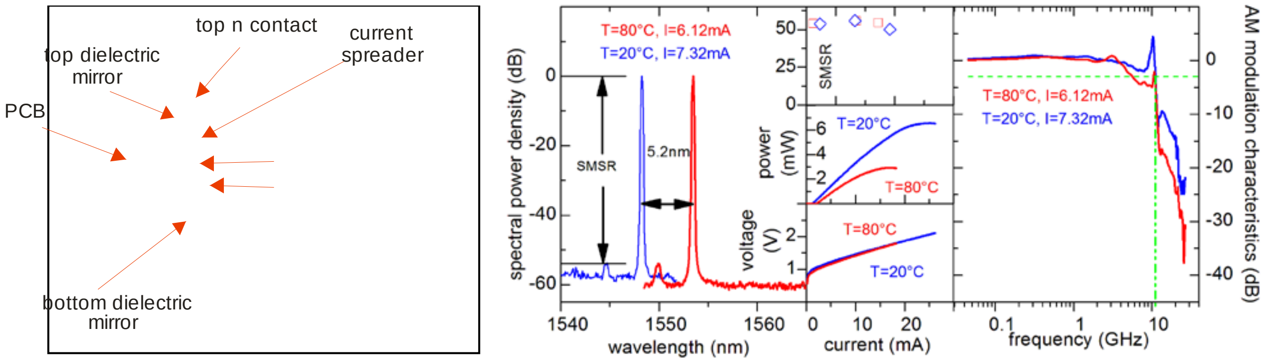

Figure 3: Schematic cross-section of a high-speed non-tunable 1.55 µm InP-based BTJ VCSEL, its spectrum, side mode suppression, power current, voltage current and AM modulation characteristics.

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.

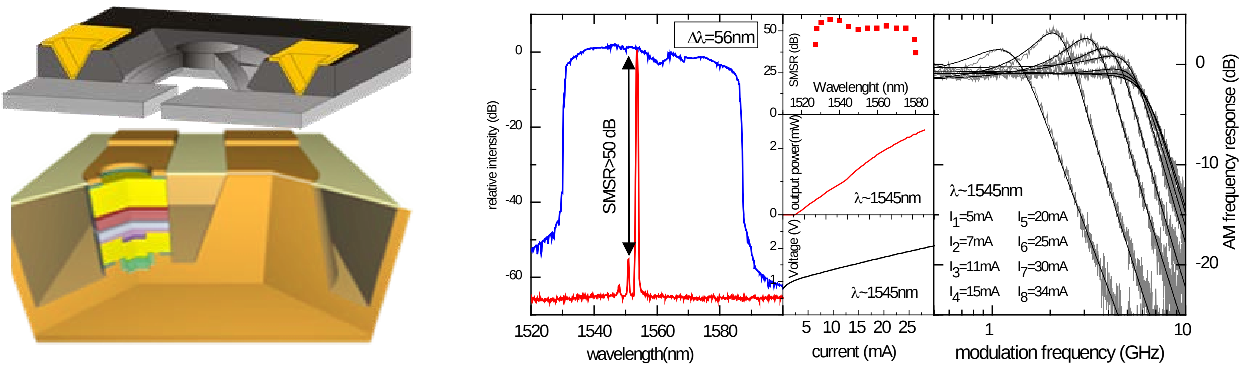

Figure 4: Schematic cross-section of a high-speed bulk-micromachined tunable 1.55 µm InP-based BTJ VCSEL, its spectrum, side mode suppression, power current, voltage current and AM modulation characteristics.

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.

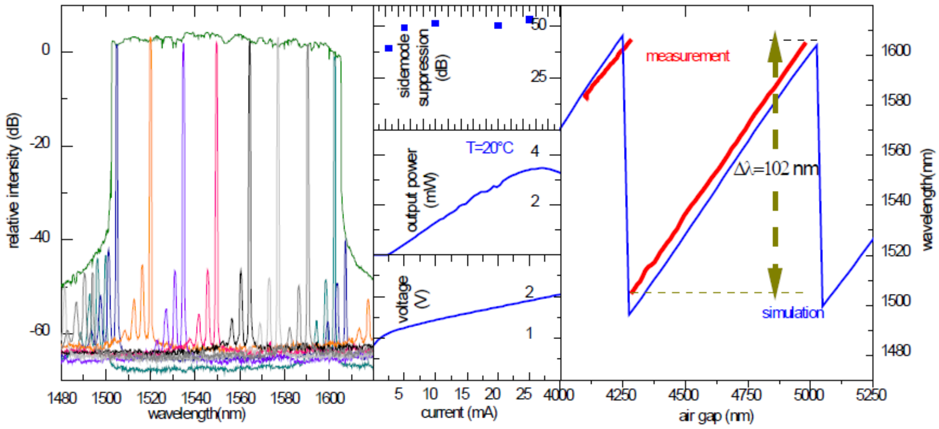

Figure 5: Tuning and power characteristics of a 1.5 µm surface micromachined tunable VCSEL

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 unpackaged VCSEL. The lasers show great promise for telecommunications applications.

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

VCSEL Specifications	Minimum Perfor-mance	Ultimate Goal	Achieved results					
			InP based			GaAs based		
Centre wavelength [µm]	0.75-2.1	0.75-2.1	1.55 µm		2.0µm	0.8µm		
			Bulk	Surface	Surface	Bulk	Surface	
							TUD	Chalmers
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	30*	X	X
Tuning range [nm]	30	60	56	102	50	37	13	24
Tuning speed [µs] (full scale wavelength switching)	1000	10	thermal 1300	thermal: 1300 electrostatic: 5	thermal: 1100	700Hz*	X	100 Hz
Tuning current [mA] or voltage [V]	20…50	10	20-40mA	20-40m 100-200	20-40mA	10-20mA	10-26mA	<16mA
Modulation frequency, bitrate [Gitb/s]	0.56	10	6GHz	X	X	3.2GHz 5Gbit/s	3.2GHz	6 GHz 5Gbit/s

Further information can be found on our website www.subtune.org