Fabrication and performance of tuneable single-mode VCSELs emitting in the 750 to 1000 nm range

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ABSTRACT

The growing demand on low cost high spectral purity laser sources at specific wavelengths for applications like tuneable diode laser absorption spectroscopy (TDLAS) and optical pumping of atomic clocks can be met by sophisticated single-mode VCSELs in the 760 to 980 nm wavelength range. Equipped with micro thermo electrical cooler (TEC) and thermistor inside a small standard TO46 package, the resulting wavelength tuning range is larger than +/- 2.5 nm. U-L-M photonics presents manufacturing aspects, device performance and reliability data on tuneable single-mode VCSELs at 760, 780, 794, 852, and 948 nm lately introduced to the market. According applications are O2 sensing, Rb pumping, Cs pumping, and moisture sensing, respectively. The first part of the paper dealing with manufacturing aspects focuses on control of resonance wavelength during epitaxial growth and process control during selective oxidation for current confinement. Acceptable resonance wavelength tolerance is as small as +/- 1nm and typical aperture size of oxide confined single-mode VCSELs is 3 µm with only few hundred nm tolerance. Both of these major production steps significantly contribute to yield on wafer values. Key performance data for the presented single-mode VCSELs are: >0.5 mW of optical output power, >30 dB side mode suppression ratio, and extrapolated 10E7 h MTTF at room temperature based on several millions of real test hours. Finally, appropriate fiber coupling solutions will be presented and discussed.

Keywords: single-mode, tuneable, spectroscopy, atomic clock, single-mode, VCSEL

INTRODUCTION

Oxide confined single-mode VCSELs are under investigation since almost 10 years [1], [2]. Due to the advantageous current confinement by wet thermal oxidation electro-optical characteristics of these devices are most attractive for applications that require close to ideal laser sources with minimized power dissipation. Two of the main applications, tuneable diode laser absorption spectroscopy and optical pumping of miniature atomic clocks are described later in this paper. The incorporation of a relatively high effective index step into the optical cavity which is unavoidable in oxide confined VCSELs results in only small active diameters that allow for single-mode operation with more than 30 dB side-mode suppression ratio. Active diameters of only 3 µm are challenging to manufacture in terms of high yields, and in addition spectroscopical use of laser sources requires precise wavelength matching, which only can be achieved by highest quality epitaxial growth control. U-L-M photonics has established epitaxial growth and processing procedures that enable controlable device production of single-mode VCSELs at various wavelengths. Further value is added by integration of micro thermal electrical coolers into the same small TO46 cans. Using these heaters/coolers, ambient temperature changes and wavelength adjustment towards absorption lines can be achieved with only small power consumption. Fine tuning of emission wavelength to absorption lines or sweeping the emission wavelength across such a line can be done by directly varying the laser current. Equipped with advanced fiber coupling solution by E2000 receptacles, the specific light can be lead to the point of use without exposing the laser unit to possibly harsh atmosphere.

FABRICATION: EPITAXY AND PROCESSING

Compared to standard datacom VCSEL technology, where multi-mode emission wavelengths within a +/- 10 nm range around 850 nm are being accepted, epitaxial growth of spectroscopy VCSEL wafers is much more demanding. Precise control of several key parameters is essential to allow for both correct emission wavelength and acceptable yield numbers which are mainly affected by homogeneity of resonance wavelength across the wafer and homogeneity of material composition of the current confinement layer.

In order to meet the targeted emission wavelength with accuracy of better than +/- 1 nm intensive calibration of the fluxes from effussion cells in the solid state MBE system is required. Due to residual variations and drifts of the growth

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parameters, it is of significant help to have an in-situ control system available that enables real-time fine adjustment of the growth rates during growth of the cavity and thus tuning of the resonance wavelength by a couple of nanometers. Advanced simulation tools that calculate according resonance profiles in parallel provide detailed target plots as can be seen on the right hand side of Figure 1. Comparing these plots with real time measurements, left hand side in Figure 1, assist the operator in tuning the resonance wavelength to the precise target value.

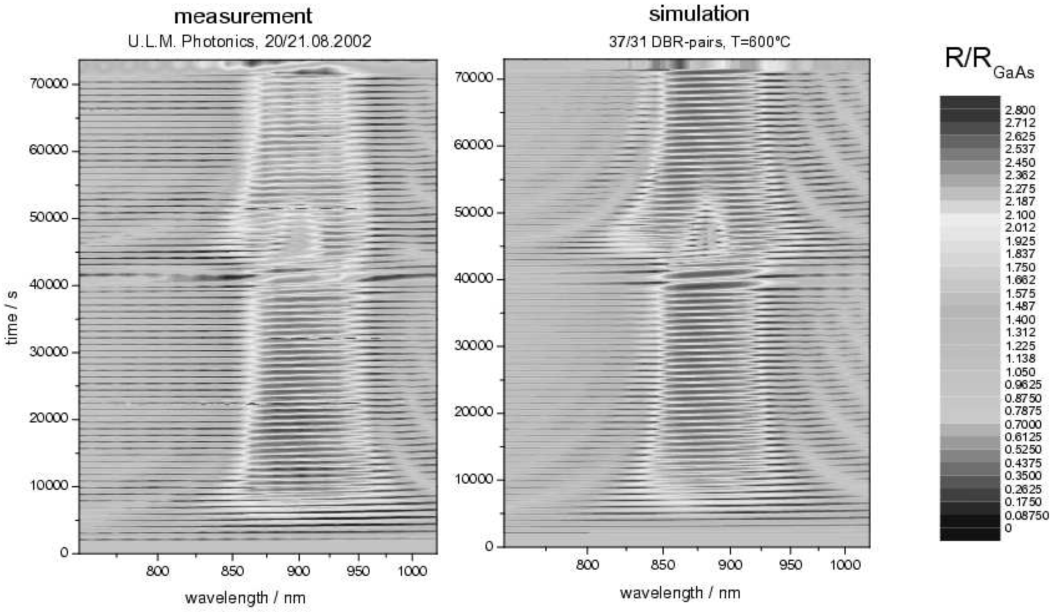

Fig. 1: Reflectivity map of optical cavity response to external illumination during epitaxial growth of a 850 nm VCSEL structure along the growth duration. Left hand side illustrates the real-time measurement of the reflectivity map, on the right hand side according simulation data are presented.

Special geometries of wafer holders and effusion cells in the RIBER 49 system result in good homogeneity of the cavity resonance across the 3 inch VCSEL wafers. Fig. 2 gives an example on the wavelength variation obtained with above mentioned technology. In azimuthal direction, the homogeneity of the resonance dip is extremely good and values stay within a +/- 0.5 nm range (+/- 0.06 %). In radial direction, variation is slightly increased and taking edge exclusion area not into account, wavelength variation amounts to +/- 1 nm (+/- 0.12 %).

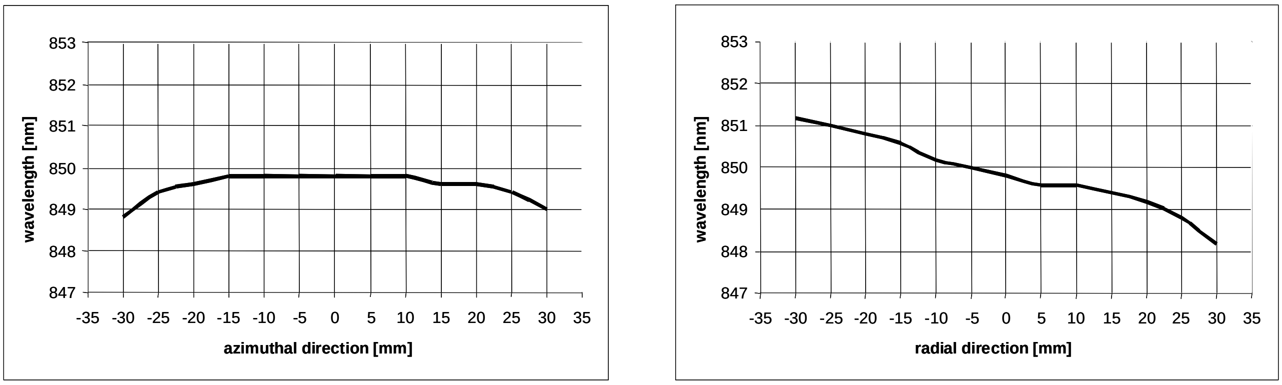

Fig. 2: Left: Azimuthal cavity resonance variation of MBE grown 850 nm VCSEL structure. Right: Radial cavity resonance variation, increasing numbers indicate larger distance to center axis of the multi wafer MBE system.

As a result, the commercial production MBE system enables control of resonance wavelengths with an accuracy of +/- 1 nm and achievable variations across the entire wafer area amount to additional +/- 1 nm.

Standard oxide confinement VCSEL technology requires small active diameters of around 3 µm [2] in order to achieve good single-mode performance of the devices. Main parameters for the oxidation process control are process temperature and material composition. Temperature homogeneity across the wafer during the formation of the apertures must be better than +/- 0.5°C. Ga content of the current blocking layer is much more crucial [3], but can be controlled very well. Oxide layer thickness is chosen to be larger than 30 nm although contribution to optical confinement is rather strong, but oxidation rates are much more sensitve on thickness variations for thinner layers [4]. Finally Carbon concentration plays an important role for the homogeneity of the current confinement layer and needs to be controlled precisely with variations of less than +/- 5 % during the growth of the current confinement layer, too. In addition to these MBE based parameters, control of the mesa diameter is of high importance, since this is defining geometrical starting conditions of the wet oxidation process. Both commonly used technologies, wet chemical etching as well as dry etching techniques provide accuracies of better than +/- 0.2 µm. Here both masking tolerances and etching process control need to be considered. Taking all mentioned aspects into account, variations of +/- 0.5 µm at typical 24 µm oxide width can be achieved (+/- 2 %). Results plotted in Fig. 3 show that no significant trends of oxide layer widths are obvious in both main axis directions.

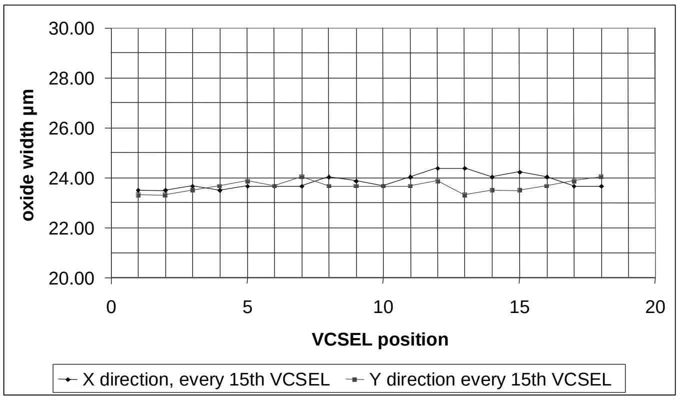

Fig 3: Oxide layer widths across a 3 inch VCSEL wafer. Target oxide width is 24 µm which is achieved with an accuracy of +/- 0.5 µm. The pitch between VCSELs is 250 µm, distance between the dots in the diagram thus amounts to 3.75 mm.

Beside residual inhomogeneity of the oxide layer width, absolut accuracy of the wet oxidation process needs to be considered. Intensive callibration of the oxidation setup results in absolut accuracy of +/- 4 % (accordingly +/- 1µm @ 24 µm oxide width). As a result, the overall tolerance of active diameter by wet oxidation processing for single-mode VCSELs is 3 µm +/- 1 µm and additionally +/- 0.5 µm of oxide width homogeneity across a 3 inch wafer. One option to compensate for this remaining tolerances is to design several devices on the wafer which differ slightly in mesa diameter. The following results are based upon a mask set layout that comprises 6 different mesa diameters und thus 6 different active diameters of VCSELs. Nominal values for active diameters are 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5 µm which cover the described processing span and allow for identification of single-mode VCSELs everywhere across the 3 inch wafer.

CHARACTERIZATION

100 % on wafer mapping of LIV characteristics is used to identify potential in spec single-mode VCSELs. Fig. 4a illustrates mapping of a single-mode VCSEL wafer. The horizontal stripes correspond to the different active diameters discussed in the last section. In this example the colours indicate values of the threshold current. Upper and lower limit of the colour coding is 0.2 and 0.5 mA, respectively.

Along both main directions of the 3 inch wafer, the variation of threshold current within nominal identical device size is very small. Devices identfied as “good die” by LIV specs are additionally investigated upon their spectral characteristics. For all such devices identified as potential single-mode VCSELs high resolution optical spectra are recorded in a second on wafer mapping. Peak emission wavelength, side-mode suppression ratio, and wavelength separation between fundamental and first higher order mode are main parameters that are recorded and evaluated. The wavelength span observed from Fig. 4b is around +/- 1.5 nm and centered at 781 nm. All measurements are carried out at RT.

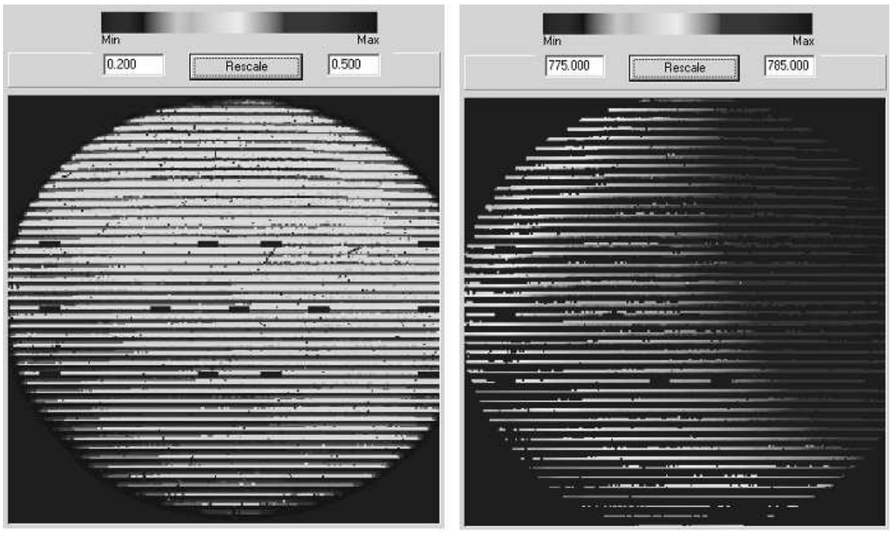

Fig 4: Left: LIV characteristics of a 780 nm single-mode VCSEL wafer. Right: Peak emission wavelength from optical spectra of a 780 nm single-mode VCSEL wafer.

From all devices that are within specification limits regarding electro-optical and spectral parameters, ensembles of VCSELs are taken for reliability testing. Only after successfully passing reliability qualification, the single-mode VCSEL wafers are qualified for selling.

LIV AND SPECTRAL PERFORMANCE

Based on same technology, all single-mode VCSELs in discussion show similar electro-optical and spectral behavior. Below 800 nm slight performance restrictions regarding slope efficiency are observed, due to incorporation of aluminum into the QWs. Specified output power at operation point thus is 0.3 mW for wavelengths of 760 and 795 nm at operation currents below 2 mA. For wavelengths of 852 and 948 nm the corresponding output power level in operation is in excess of 0.5 mW.

Fig. 5 shows LIV data and optical spectrum of a 759 nm single-mode VCSEL. Typical threshold current is as low as 0.4 mA and 0.3 mW is reached at 1.2 mA laser current. Corresponding operation voltage is 2.0 V. In the optical spectrum on the right hand side ideal single-mode behavior can be seen. Side-mode suppression ratio (SMSR) is around 40 dB and thus much better than specified 30 dB. Spectral separation of fundamental and first higher order mode is 0.8 nm which is one of the selection criteria for single-mode products. Smaller and thus less reliable single-mode VCSELs show much larger spectral separation between these modes [5] and can be rejected based on this parameter although they fulfill all other electro-optical parameters. 760 nm single-mode VCSELs are mainly used for oxygen concentration analysis.

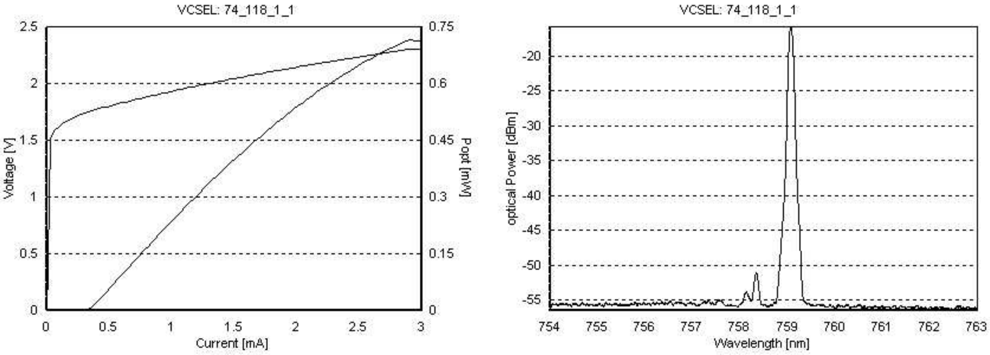

Fig. 5: LIV (left) and optical spectrum (right) of a 760 nm single-mode VCSEL. All measurements are carried out at RT.

In Fig. 6 the LIV performance graph of a 948 nm single-mode VCSEL is depicted. 0.3 mA of threshold current and 0.7 W/A slope efficiency are outstanding performance data for this type of device. At 0.5 mW output power operation current is only 1.0 mA. At this laser current SMSR exceeds 30 dB easily. Again spectral mode separation is checked and found to be 1.1 nm. 948 nm single-mode VCSEL find their application in moisture concentration sensing of e.g. natural gas.

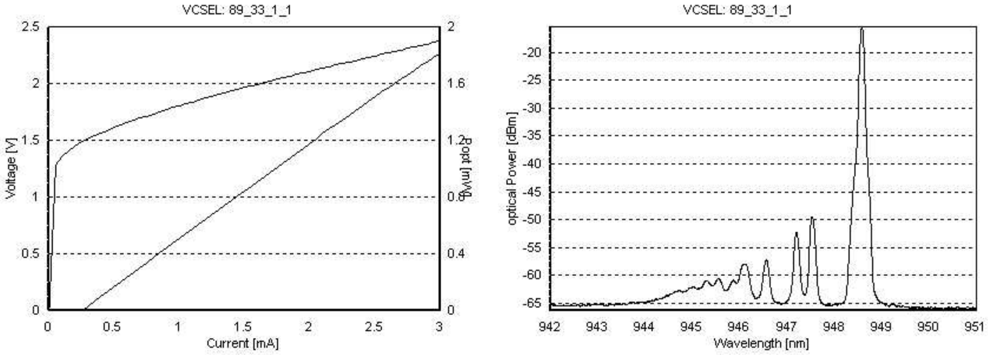

Fig. 6: LIV (left) and optical spectrum (right) of a 948 nm single-mode VCSEL. All measurements are carried out at RT.

Electro-optical performance of a 795 nm single-mode VCSEL is almost identical to already discussed 760 nm VCSELs. Threshold current and operation point are 0.4 mA and 1.4 mA, respectively. SMSR is better than 30 dB and spectral mode separation is around 0.8 nm. Miniature atomic clocks require small size optical pumps emitting at absorption lines of Rb or Cs atoms. 795 nm single-mode VCSELs are designed to optically pump Rb based atomic clocks.

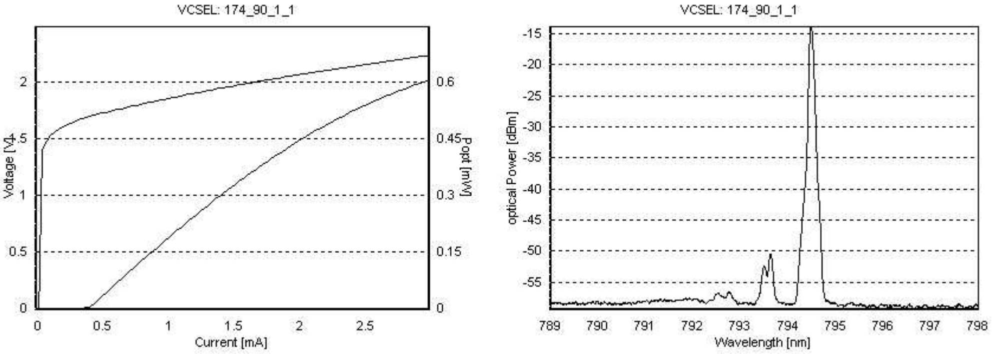

Fig. 7: LIV (left) and optical spectrum (right) of a 795 nm single-mode VCSEL. All measurements are carried out at RT.

Cs is another basis for miniature atomic clocks. Optical pumping wavelength can be 852 nm. Corresponding single-mode VCSEL performance is illustrated in Fig. 8. 0.4 mA threshold current and 0.5 W/A slope efficiency results in 1.4 mA operation current at 2V applied voltage. SMSR is better than 40 dB and mode separation is 1.3 nm.

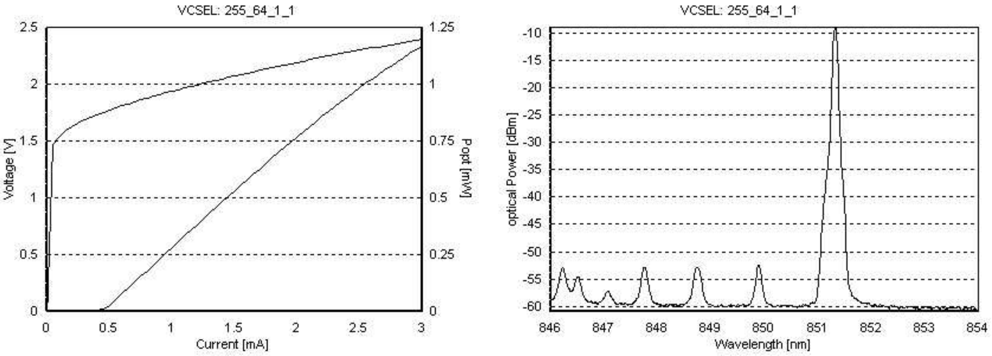

Fig. 8: LIV (left) and optical spectrum (right) of a 852 nm single-mode VCSEL. All measurements are carried out at RT.

RELIABILITY

Since more than 16 months, accelerated lifetime measurements are ongoing for 760 nm single-mode VCSELs which are regarded as most critical in terms of reliability due to their high aluminum content in the multi layer VCSEL structure. Up to now, no final MTTF values can be extracted since the ensemble of devices did not fail yet. The data points in the arrhenius plot given in Fig. 9 are therefore worst case assumptions. Each dot corresponds to 31 devices in operation at constant current of 2 mA. In total 279 devices are under test, more than 3 Mio real test hours have been collected so far. MTTF values are ploted against junction temperatures, which are calculated from the sum of accelerated ambient temperature and internal self heating due to dissipated power. Current density scaling effects are thus already implemented in the data. The dashed line indicates the typical guideline for U-L-M photonics' 2nd generation oxide confined VCSEL products. Activation energy of 0.7 eV is assumed to be the same as for all other products based on the same technology. Extrapolated MTTF value at RT is ~10E7 h.

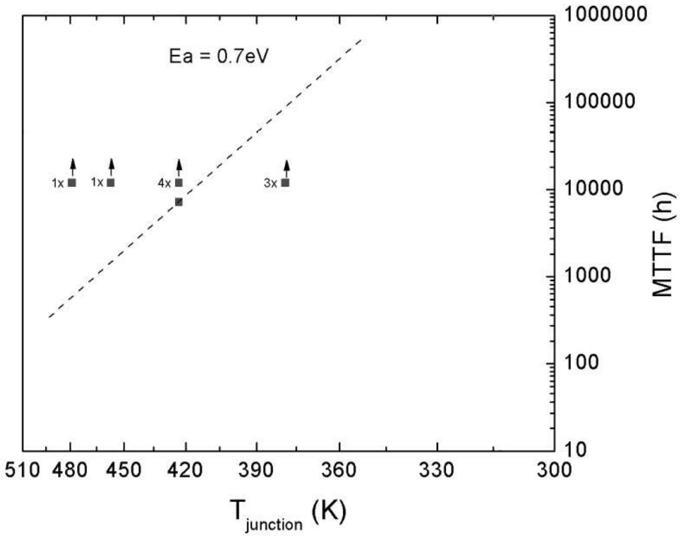

Fig. 9: Arrhenius plot of MTTF values versus junction temperature. Each dot corresponds to one or multiple ensembles of 31 VCSELs. The arrows indicate that after 12.000 h of operation at ambient temperatures of up to 170°C measurements are still ongoing and MTTF values are worst case estimations so far.

SINGLE-MODE FIBER COUPLING

Several applications require fiber coupling solutions for spectroscopy VCSELs, especially if measurements need to be taken in harsh and hostile atmosphere. In tunable diode laser absorption spectroscopy, which will be discussed in the following section, optical back reflection dramatically limits the sensitivity of the measurement. Therefore optical feed back levels must be minimized. Using special ball lens coupling techniques and AR coatings, low back reflection levels have been achieved. Anyway, coupling efficiencies to 5 µm core diameter single-mode fibers remain in the 30 % range. The use of E2000 receptacles offers both, repeatable and efficient fiber coupling to single-mode fiber as well as comfortable system implementation. Fig. 10 shows such an E2000 receptacle, in which the hermetically sealed TO46 package (on right hand side in the picture) is aligned and fixed by laser welding.

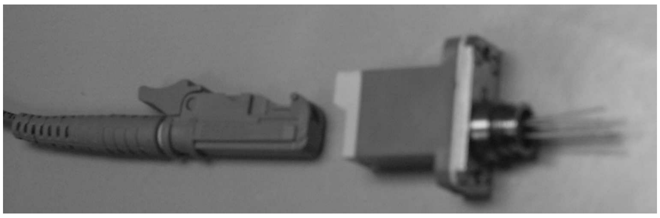

Fig. 10: E2000 receptacle with single-mode VCSEL coupled to 5 µm core diameter single-mode fiber. Coupling efficiency is qualified to more than 30 %.

APPLICATIONS

Currently, two main applications are supported by single-mode spectroscopy VCSELs: Tuneable Diode Laser Absorption Spectroscopy and optical pumping of atomic clocks.

TDLAS is a well known technique for measuring gas concentration fast and over a wide range of concentration levels. Corresponding laser sources are key components in these systems. The laser wavelength must be adjustable to the absorption bands of the gases, and the emission wavelength must be tuned across such an absorption line in order to record characteristic absorption behavior. The demand on compact and unexpensive systems in order to compete with non optical sensors, like paramagnetic oxygen sensors, favours VCSEL technology for this application.

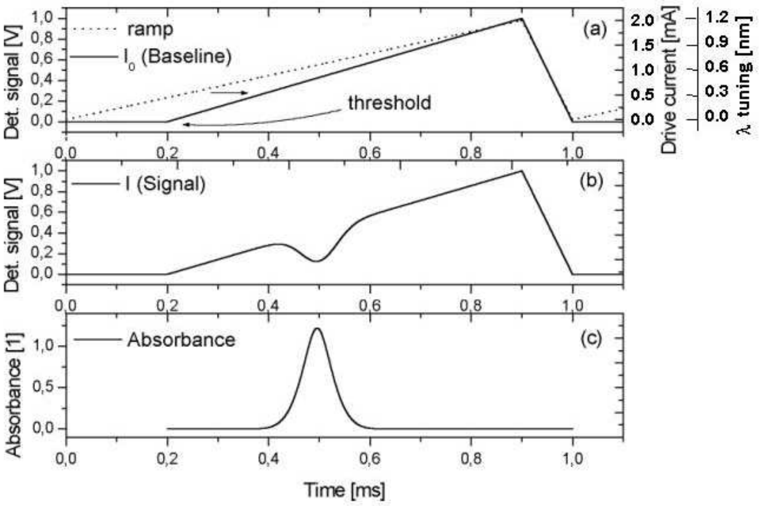

Fig. 11: Top: increase of laser current and output power with time. According to 0 to 2 mA current sweep, wavelength is increased by typically 1.2 nm. Center: Scanning the wavelength across the absorption line results in a dip in linear power increase. The depth of the dip is dependent on gas concentration. Bottom: Absorbance values can be computed from the detection signal and provide information on present gas concentration. (based on [6])

Main advantage of VCSEL technology for TDLAS is the low power consumption, fast response time when tuning the laser wavelength, and the advantageous beam profile of the VCSEL which is beneficial for both, fiber coupled solutions and free space systems. In addition, smaller frequency drift over time has been shown in comparison with Fabry-Perot or DFB lasers [7].

In combination with a micro TEC that can be placed into the same tiny TO46 can, single-mode VCSELs are most attractive tuneable spectroscopy laser sources. Due to the low thermal mass of the VCSEL/TEC subsystem, fast temperature changes of up to +/- 40 °C can be achieved with relatively low power consumption of less than 100 mW for the TEC. This temperature range results in a +/- 2.4 nm wavelength tuning range, which is used to adjust the laser wavelength to a certain absorption line. A closed control loop can be established by using the internal thermistor, which is also placed in the TO46 can close to the VCSEL chip. Internal laser heating due to dissipated power additionally changes laser emission wavelength. Along the maximum current range above threshold of 0.5 to 2.0 mA, wavelength tuning of 0.9 nm can be achieved. By sweeping the laser current and thus laser wavelength across a single or multiple absorption lines, characteristic absorption data can be recorded that enable accurate and highly sensitive concentration measurements. All together a maximum wavelength tuning span of 5 nm can be covered using both tuning mechanisms. Wavelength tuning characteristics by TEC current and laser current is presented in Fig. 12. TEC currents of 0, 25, 50, 75, 100, 150, and 200 mA are applied to cool down the laser and result in a maximum wavelength offset of -1.2 nm which increases linearly with TEC current. Accoding temperature drop at 200 mA TEC current is 20 °C and the resulting tuning parameter is 0.006 nm/mA. When increasing the laser current from 0.5 up to 2 mA, a 1.0 nm wide wavelength sweep can be achieved.

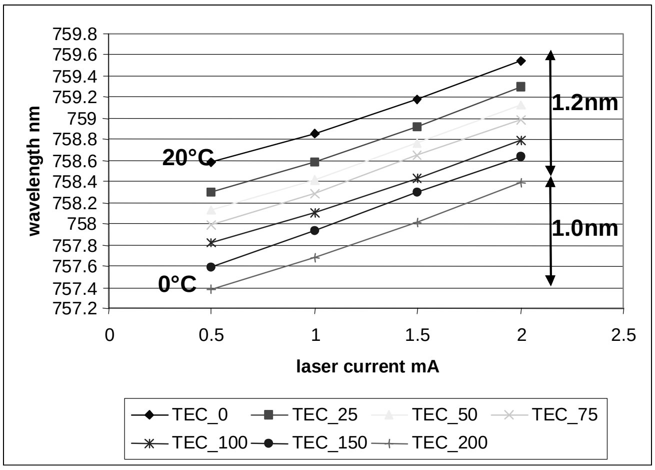

Fig. 12: Tuning range of a 760 nm single-mode VCSEL. Micro TEC temperatue control is used to tune the VCSEL to a certain wavelength level. The individual straight lines correspond to 0, 25, 50, 75, 100, 150, and 200 mA of TEC current, according wavelength is decreasing linearly by 1.2 nm. The 0.6 nm/mA redshift of emission wavelength with increasing laser current is used to sweep the wavelength across the absorption line.

Optical pumping of miniature atomic clocks by VCSELs is a new approach to provide extremely small but high performance clocks for low cost GPS systems or synchronization in data networks. Several groups [8], [9] have already demonstrated VCSEL based small volume clocks, using either Cs or Rb atoms. Corresponding optical pump wavelengths are 852 for Cs and 780 or 795 nm for Rb, respectively. Fig. 13 shows a picture of an atomic clock that is pumped by VCSEL power. Overall height of the vertical assembly is only 4.2 mm, including all major components like VCSEL pump, optics, Cs cell and photodiode [8].

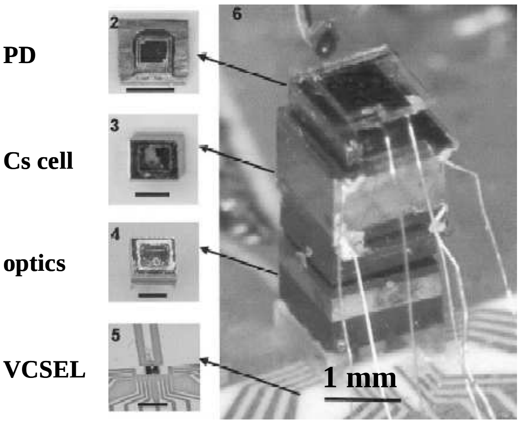

Fig. 13: Miniature atomic clock, optically pumped by a single-mode VCSEL. [8]

SUMMARY

Advanced manufacturing techniques have been introduced that enable production of oxide confined single-mode VCSELs with small active area. Precise wavelength control by in-situ monitoring during epitaxial growth guarantees for exact matching to targeted absorption lines. Within the 750 to 1000 nm wavelength span that can be covered by the InGaAlAs material system, performance of single-mode VCSELs at various wavelengths is comparable. High spectral purity and tuneability by a micro TEC makes those devices very attractive for application in TDLAS and miniature atomic clocks. Additionally, the small TO46 package and extremely low power consumption is a plus for compact system integration

Further improvements in manufacturing of single-mode VCSELs will include increase of the active area by optical cavity design and advanced processing that will provide smaller process tolerances.

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