VCSEL MEASUREMENTS AND CHARACTERIZATION FOR GAS SENSING

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Abstract: *The paper presents the results of measurements and analysis of parameters and characteristics of Vertical Cavity Surface Emitting Laser (VCSEL) Diode to use in gas detectors on the basis of the tunable diode laser spectroscopy method. Precise absorption spectra were obtained to determine the optimal wavelengths for gas sensing. The measurement results showed that the possibility of increasing the output power of VCSEL by enlarging the diameter of the tunnel junction being limited by the increase of the number of modes in the emission spectrum. The analysis of the encapsulated VCSEL modules had demonstrated high SMRS (above 40 dB), high temperature stability of the emission wavelength ($d\lambda/dT \approx$ 0.05–0.08 nm/K), possibility of continuous change of emission wavelength with operation current, which allows efficient use of VCSEL for ammoniac detection by TDLS method.*

Key words: *Gas Detector, Vertical Cavity Surface Emitting Laser Diode*

I. Introduction

Many gases have characteristic absorption lines in the infrared wavelength region. A widely favored approach to accurate and sensitive gas concentration measurement is the tunable diode laser spectroscopy (TDLS). In order to determine the gas concentration with TDLS, a single-mode, tunable diode laser is wavelength - centered onto one of the fine absorption lines of the target gas. The laser is driven to obtain wavelength modulation and scan absorption lines within a very narrow range. Absorption of infrared light with specified wavelength by the target gas molecules leads to a decrease of intensity on a detector, depending on the gas concentration. Detection of the photocurrent at the original modulation frequency and some related frequency significantly reduces the noise by shifting detection to higher frequencies where laser source noise becomes negligible and removes much of the baseline slope found in direct absorption [1].

Laser Diode for TDLS has to processes: single-mode optical emission; sliding wavelength; high efficiency; low divergence; low power consumption; high stability over the temperature; low cost. We studied the parameters and characteristics of the Vertical Cavity Surface Emitting Lasers (VCSELs) to estimate the features and their applications in gas detection and the TDLS method.

In contrast to conventional stripe lasers, VCSELs are designed to ensure the vertical output of emission, normal to the plane of the semiconductor substrate. Distributed Bragg reflectors (DBRs) are used as the top and bottom mirrors confining the vertical Fabry–Perot cavity. Owing to their symmetrical configuration and the relatively large (several micrometers) size of the emitting region, VCSELs have a significantly narrower and more symmetric emission pattern than the stripe lasers. Due to the fact that the emission wavelength can be tuned continuously with diode current over several nanometers (the precise wavelength can be set either by changing the cavity length or by temperature tuning), VCSELs have a considerable advantage compared with edge emitting lasers for sensing applications. However, many applications of long wavelength VCSELs operating in the 1.5 µm waveband require significant high output power.

The VCSEL device structure (schematically presented in Figure 1) consists of an InP-based active cavity, which includes multi-QW region with compressively strained quantum wells and a tunnel junction. The active cavity is fused between undoped GaAs/AlGaAs distributed Bragg reflectors (DBRs) with very high reflectivity. The InP-based active cavity and GaAs-based DBRs are grown by low pressure metal-organic vapour phase deposition. A mesa-structure formed in the tunnel junction, which is re-grown with n-type InP, serves for carrier and photon confinement. Electrical contacts are performed on the top and bottom intra-cavity n-InP layers. This contacting scheme allows using un-doped top and bottom DBR mirrors. [2,3].

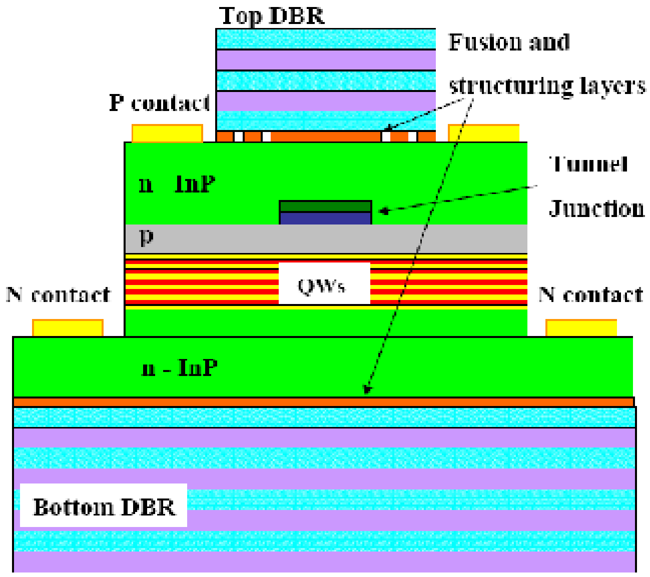

Fig.1. Schematic representation of VCSEL structure with regrown tunnel junction.

The measured absorption spectrum of NH_3 shows the possibility of using lasers with different wavelengths emission in the range of 1490-1550 nm for NH_3 detection, where NH_3 absorption prevail over other gases.

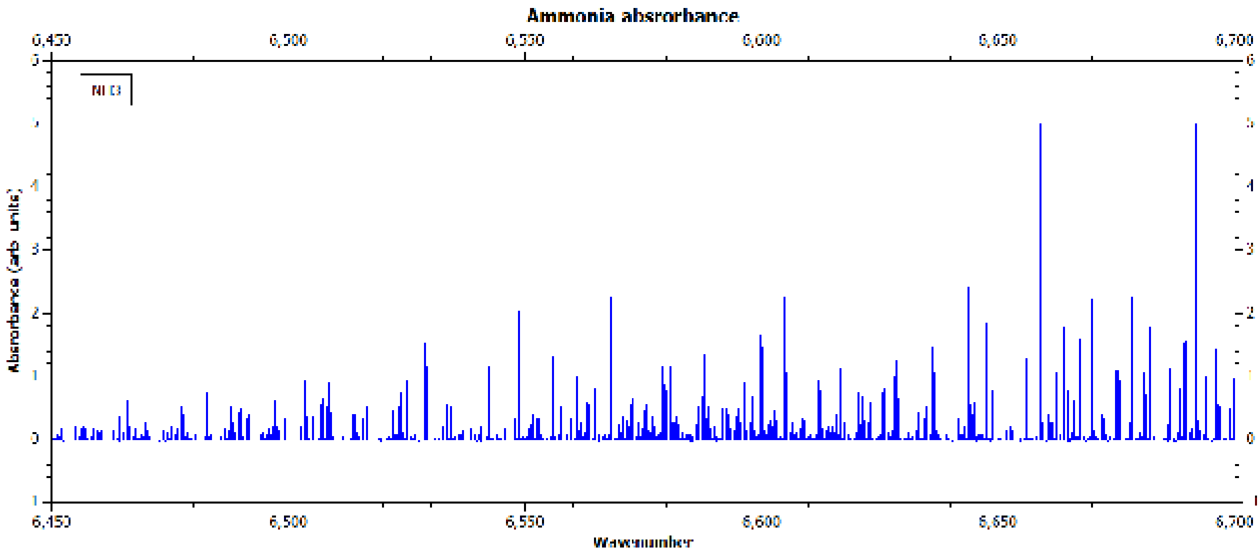

Fig.2. The measured with high precision absorption spectrum of ammoniac in the range of 1490-1550 nm (6450 – 6700 cm^{-1}).

II. Characterization of VCSEL with different size of tunnel junction

The parameters and characteristics of VCSEL structures with different diameters of the tunnel junction were measured and studied to study the possibility of increasing the single chip emission power. The output optical power and mode profiles of this VCSEL design are defined by the tunnel junction mesa diameter.

The measurements of volt-ampere characteristics and watt-ampere characteristics (L-I-V) had been carried out for a VCSEL with different diameters of the tunnel junction (7µm, 10µm, 15µm, 20µm, 25µm, 35µm, 40µm, 45µm, and 50µm). All the measurements had been carried out for the chips of laser devices at 20°C temperature value. Some of the results are shown in figure 3.

The obtained results showed an essential increase in the maximum achievable emission power with the increasing diameter of the tunnel junction. The maximum emission power is reached for

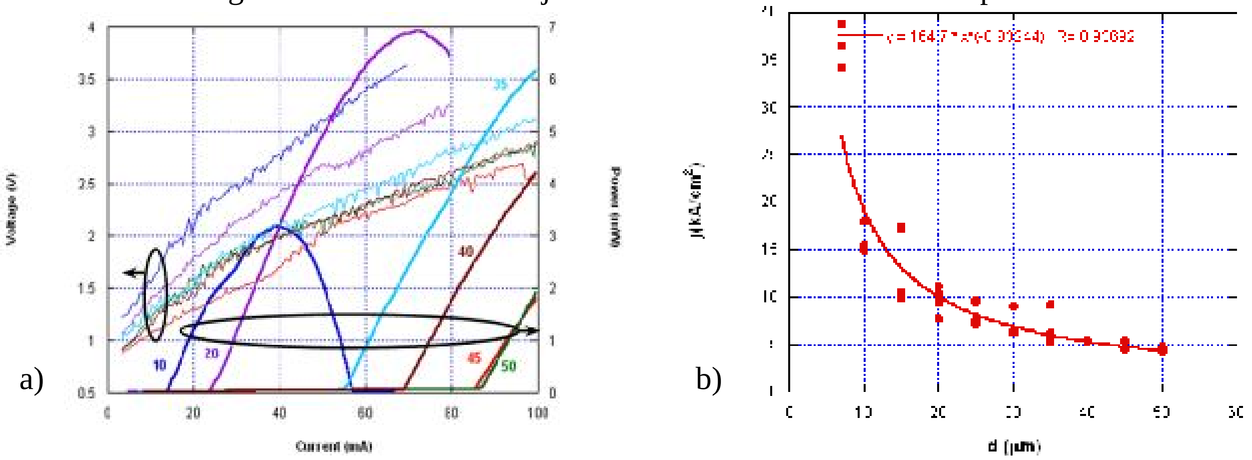

Fig.3. a) LIV characteristics for VCSELs with different diameters of the tunnel junction;
b) Dependence of the threshold current density on tunnel junction diameter.

the laser devices with the tunnel junction diameter values 20µm and 35µm, because the LIV characteristics are presented at the operating current values up to 100mA. The VCSEL lasers with a tunnel junction diameter bigger than 40□m had not shown satisfactory emission characteristics at these current values. All the measured parameters had been processed and it was determined the value and the dependence of the threshold current density on the tunnel junction diameter for the VCSEL lasers (figure 3,b). It is evident from figure 3,b that the threshold current density decreases with the tunnel junction diameter increase. The lowest measured value of the threshold current density in the frame of this VCSEL design is for the tunnel junction diameter value of 50µm.

After measuring the VCSELs there were selected the devices with maximal emission power at each series of the tunnel junction diameter. Repeated measurement of LIV characteristics had been carried out for these samples at 5°C, 15°C, and 30°C temperature values in order to determine the operating regime at temperature variations. Some of the results are shown in figure 4,a. We can see the emission power decreases on the temperature.

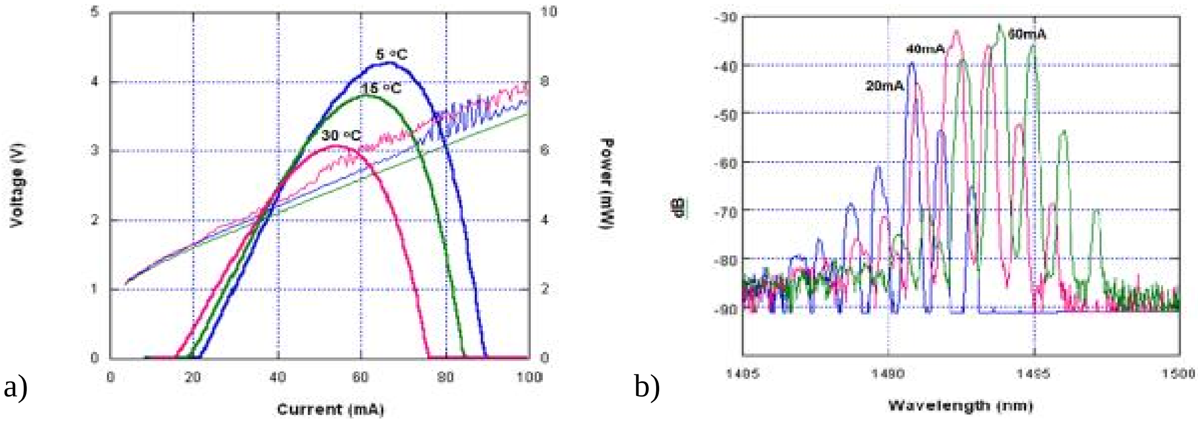

Fig.4. The characteristics for samples with the tunnel junction diameter 15µm:
a) LIV at 5°C, 15°C, and 30°C temperature values;
b) Emission spectra at 20 mA, 40 mA and 60 mA (room temperature).

The measurements of the emission spectra for different values of the operating current had been carried out for several samples that possess low threshold current values and high emission power values at room temperature (figure 4,b). The measurement results had shown stimulated laser emission in the wavelength interval 1490 - 1495nm, for the measurement carried out at the applied current values in the 20mA - 70mA range. The lasers show a strong multimode emission regime at any applied current values higher than threshold value, which is not acceptable for gas detection.

III. The wavelength stabilization of VCSEL chips

The LIV characteristics of VCSEL chips had been created for a wider operating temperature range (5°C, 10°C, 15°C, 30°C, and 50°C) in order to determine the maximum output emission power and threshold current. The result (figure 5,a) demonstrates that the optimal temperature regime for a satisfactory functioning of VCSEL lasers represents the temperature values not higher than 30-40°C if taking into account the usage in gas sensors. The emission power decreases essentially at temperature values higher than 50°C, which will show a substantial decrease of the received emission power in the gas sensor model.

The emission spectra measurements had been carried out for several samples of the VCSEL chips, which possessed single mode and maximum emission power values in order to determine the value of the applied current and operating temperature values for stabilization of the VCSEL laser emission around the 1512 nm wavelength value. The obtained results (figure 5,b) show that a single mode emission regime of the studied VCSEL lasers is present for the current values in the 5mA – 11mA range and the operating temperatures in the 15 – 25°C range.

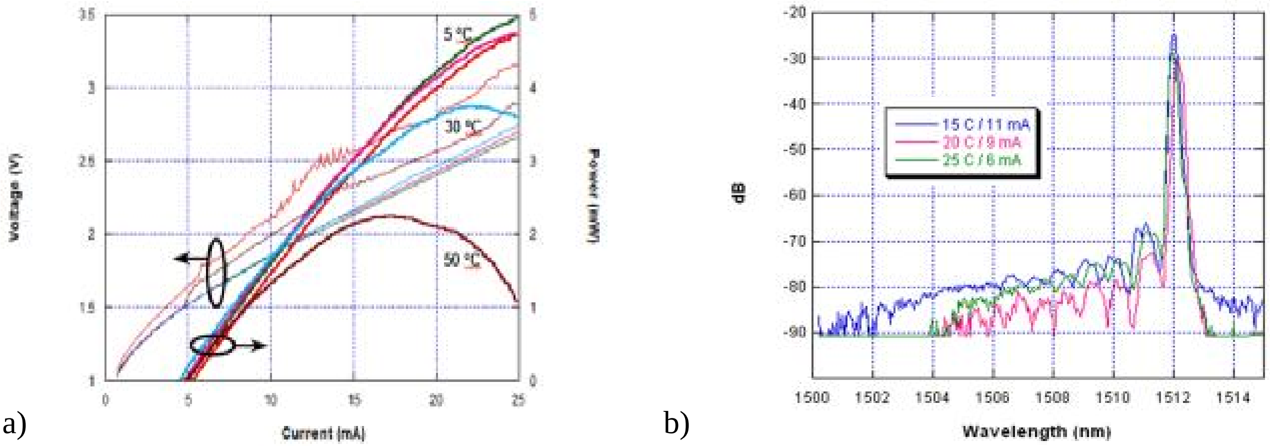

Fig.5. a) LIV characteristics at the operating temperature values 5°C - 50°C;
b) Determination of the operating temperature and applied current values for stabilization at 1512nm emission power of VCSEL chip.

IV. Measurements and characterization of encapsulated VCSEL modules

The encapsulated VCSEL module contains a photodiode for monitoring the emission power, thermistor and TEC for monitoring and controlling temperature of the chip. The modules were mounted on a stage in a setup used for measuring the emission spectra at operating current variations in the 5 - 15mA range, with a 1mA step and temperature values 17°C, 20°C, 22°C. A collimating lens was used in the measurement setup for concentrating the laser spot emitted by the VCSEL module. The measurement setup is shown in figure 6.

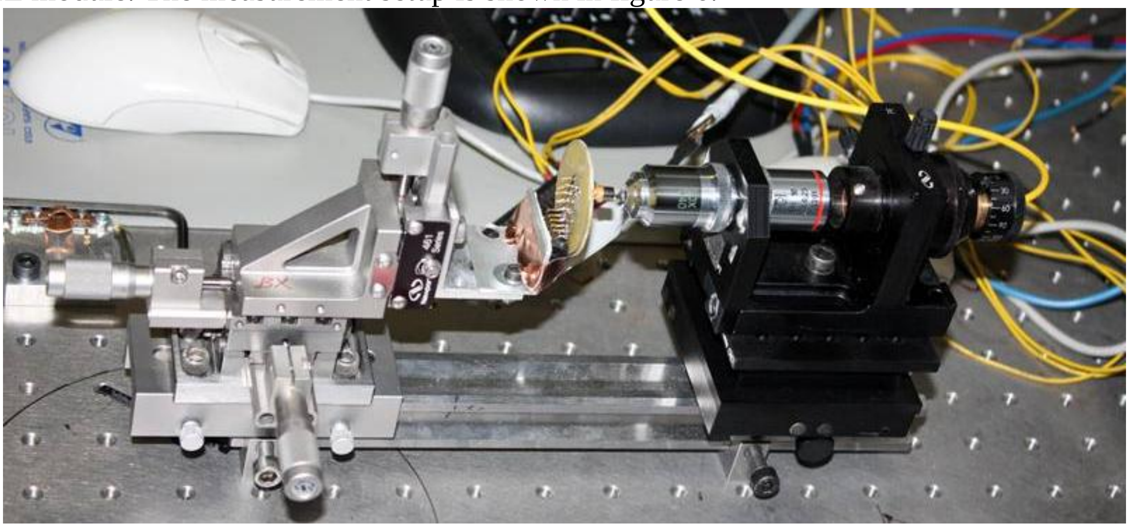

Fig.6. Measurement setup for the encapsulated VCSEL module.

During repeated measurements it was observed that the VCSEL is very sensible to the optical feedback of the mounted setup used. The optical path between the laser and the photodetector, the setup mirrors and the internal mirrors of the photodetector influence considerably the operation of the VCSEL, working as an external optical resonator and imposing the generation and amplification of several modes in the obtained spectra that correspond to the external resonator. If shortening the distance (i.e. the optical path) between the photodetector and laser it was observed that the number of amplified modes decreased. Different leaser modes and external resonator modes were being amplified at different time values, which lead to instability of the emission.

The encapsulated VCSEL modules were mounted on a stage in a setup used for measuring the emission spectra at operating current in the 5 - 15mA range and temperature values 17 - 22°C (figure 7,a). VCSEL module has a collimating lens in top of capsulate which changes conditions for concentrating the laser spot by collimating lens in the measurement setup and reduce input fiber optical power. Measured emission spectra and LIV characteristics are presented in figure 7.

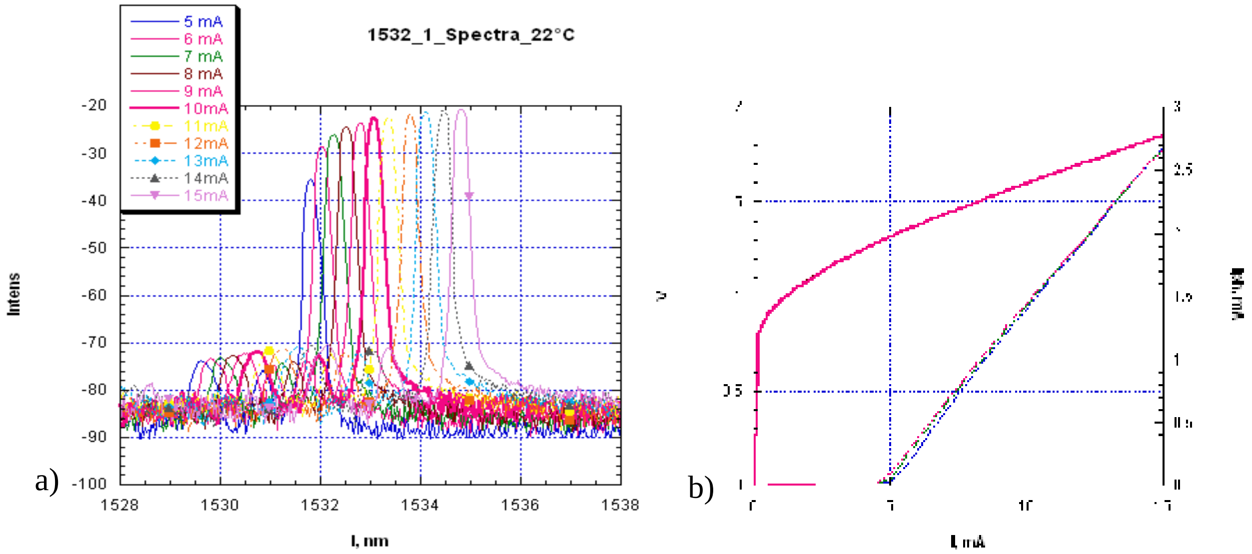

Fig.7. Characteristics of the VCSEL module:
a) Emission spectra at operating current values 5 – 15mA and 22°C;
b) LIV at 17 – 22°C.

The increase of the operating current from 5mA up to 15mA has demonstrated a variation of the emitted wavelength in the range of 1531.7 – 1534.8 nm at the temperature 22°C that is enough for gas absorption line scanning. The results show that the temperature variation in the range of 17°C – 22°C does not influence considerably the emission spectra of the VCSEL module.

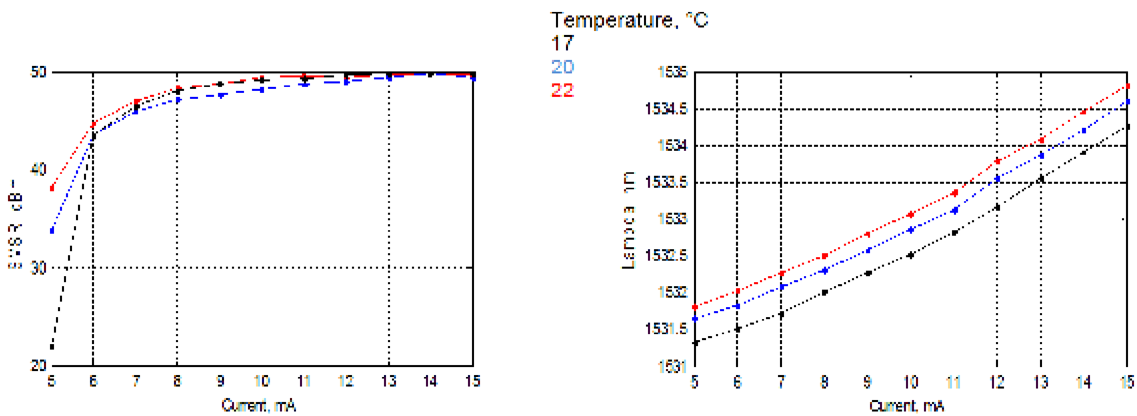

Fig.8. Dependence of the SMSR (a) and emission wavelength (b) on the current at temperature values 17°C, 20°C and 22°C

All the measured characteristics had been processed and it was determined the dependence of Side-Mode Suppression Ratio (SMSR) and the emission wavelength on the operating current for the VCSEL module at temperature values 17°C, 20°C, 22°C (figure 8). The SMSR is above 40 dB at the operating current more 6 mA for given temperatures and emission wavelength is shifted about 0,05-0,08 nm/K.

This VCSEL module can be used for ammoniac sensing (absorption band about 1532-1534nm) at range of operating temperature 17°C – 25°C and current 6-15mA (threshold current 5mA).

V. Conclusions

To increase the output power were studied parameters and characteristics of the VCSEL chips with different diameters of the tunnel junction. In terms of increasing the emission power the optimal tunnel junction diameters at operating current to 100 mA had demonstrated to be in the 10 - 30 □m range. Temperature influence on the emission power and operating regime was studied. The emission spectra of the VCSEL chips with different diameters of the tunnel junction had shown stimulated laser emission for measurement carried out at the applied current values in the 20mA - 70mA range. The structures with diameter of the tunnel junction more 10 µm show a strong multimode emission regime at anyone applied current values higher than threshold value, what is not acceptable for gas detection.

After measuring the LIV characteristics and emission spectra of the VCSEL chips at different operating temperature and current values it was estimated an optimal operating regime to stabilize the emission wavelength by correlation of current and temperature at 1512nm wavelength value in the 7 - 11mA current range and 15-25°C temperature range.

The measurements carried out on the encapsulated VCSEL modules had demonstrated high SMRS (above 40 dB), high temperature stability of the emission wavelength ($d\lambda/dT \approx 0.05–0.08$ nm/K), possibility of continuous change of emission wavelength with operation current, what allows efficient use of VCSEL for ammoniac detection by TDLS method. After measuring the spectra, LIV characteristics of the VCSEL module at different operating temperature and current values it was estimated an optimal operating regime for ammoniac detection at 1532nm wavelength value in the 7 - 15mA current range and 15-20°C temperature range.

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