VCSE diode laser emission characterized by high resolution FT spectrometry

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ABSTRACT
The main target of this work is focused on characterization and measurement of the basic properties of laser emission (laser width) of several VCSEL diode based on GaSb matrix, which are emitting in the infrared region around 4250 cm^{-1}. High resolution Fourier transform Bruker IFS 120 HR spectrometer with maximum resolution 0.003 cm^{-1} wasused for the laser diagnostic research.

Keywords: vertical-cavity surface-emitting laser diode, FTIR spectroscopy, GaSb laser, emission, absorption spectroscopy, semiconductor laser diagnostic.

1. INTRODUCTION

Laser spectroscopic techniques have a number of advantages in the study of the absorption spectra of gaseous molecules. The use of lasers and techniques based on their application, e.g. cavity ring down [1,2] or photoacoustic detection [3], has significantly increased the detection sensitivity in measuring the weak signals of molecules with a low absorbance of molecules at very low concentration.

This work was intended to study the potential application of laser absorption detection in the monitoring of formaldehyde in the region around 2.3 μm using multiple quantum well (MQW) GaInAsSb/AlGaAsSb diode lasers [4-6] . MQW GaInAsSb/AlGaAsSb based laser diodes (LDs) operate at room temperature in the mid infrared region. The structure of LDs allows us to tune the radiation with high spectral purity and to work generally in a single mode regime. LDs provide a continuous wave emission in a spectral interval of several tens of reciprocal centimetres, a sufficient output power of more than 1 mW with low optical noise. The high speed of wavelength tunability of the LDs by drive current may be used for the monitoring of fast absorption processes. The relatively high power (in comparison with the infrared LEDs) allows the replacement of the standard direct absorption method by resonant photoacoustic detection.

PA detection in combination with LDs was chosen as a simple and inexpensive method suitable for the detection of highly (rotation-vibration) resolved spectra of the gas molecules. The photoacoustic method was applied recently in our studies [5-11]. The investigation of gas detection techniques and the development of rugged and inexpensive gas sensors to monitor urban environments, industrial emissions or in applications for the control of industrial processes are of considerable interest. Widely-used near infrared or infrared absorption and photoacoustic detection in combination with simple, tunable, room-temperature operating diode lasers are very simple, cheap and promising techniques, but as yet they have not achieved the sensitivity of fluorescence measurement in the visible spectral range [12]. Further developments and studies are necessary to improve the detection sensitivity in this research field.

2. EXPERIMENTAL

2.1 GaInAsSb/AlGaAsSb diode laser

The structure of the GaInAsSb/AlGaAsSb diode laser was prepared at Montpellier by MBE and consists of three GaInAsSb/AlGaAsSb quantum wells, sandwiched between AlGaAsSb barrier layers with varied composition, GaSb substrate and GaSb contact and buffer layers [13, 14].

In order to obtain mono-mode emission at the desired wavelength, the ridged-stripe contact structure was provided with a passive distributed feedback (DFB) element by electron lithography and the chip was mounted and encapsulated at Nanoplus–Nanosystems and Technologies GmbH, Oberer Kirchberg, Gerbrunn, Germany.The laser was placed in a Thorlab TCLDM9 cold head connected to a home-made temperature control module working in the 253 to 353 K temperature range. The laser was current-controlled using a Laser Photonics L5731 unit for 50 Hz to 1 kHz or L5820 unit for 1-10 kHz. The modal characteristics of the laser were studied using high resolution Fourier transform emission spectroscopy in a temperature range of 273–333 K up to the maximum current of 120 mA.

2.2 VCSEL GaSb diode laser

The new type of VCSEL GaSb based diodes for the 4250 cm^{-1} wavelength region has been developed. The laser structures were prepared by the epitaxial growth on n-type GaSb, which is in touch with the n-contact at the bottom. A Bragg epitaxial mirror with 99.8 % reflectance is placed on this substrate and consists of twenty four couples of layers AlAsSb/GaSb. The active zone of the lasers consists of five 10-nm-thick $Ga_{0.65}In_{0.35}As_{0.1}Sb_{0.97}$ quantum wells surrounded by $Al_{0.35}Ga_{0.65}As_{0.03}Sb_{0.97}$ barriers. The p-contact has an opening for the outgoing laser beam through the buried tunnel junction and covers laser structure from above. The dielectric mirror from four couples of layers Si/SiO_2 with reflectance 99.7 % is placed at the top of the laser structure above the buried tunnel junction. The emission wavelength of the lasers can be varied by changing the active-region structure. Fine tuning of these single-mode lasers can be easily realized by changing the operating temperature and the injection current. Lasers operate in the continuous-wave (CW) regime at laboratory temperature with the output power around 50 μW. The obtained value of the threshold current is around 1.5 mA and its temperature dependence is weak.

2.3 FTIR spectroscopy

High resolution Fourier transform spectroscopy was used in the following experiments:

a) The spectrum of methane, ammonia and formaldehyde used for calibration of the experiments was measured using a FTIR Bruker IFS 120 HR spectrometer in absorption mode. An absorption cell with KBr windows, of length 26.5 cm and a diameter 5 cm, was filled by formaldehyde up to 1 Torr. The gaseous formaldehyde (produced by heating of paraformaldehyde) was measured in a spectral range of 1800-6500 cm^{-1} using a near infrared spectral source of radiation, CaF_2 beamsplitter and InSb detector. In all, 50 scans were coadded with resolution of 0.01 cm^{-1} and apodized by the Blackman-Harris 3-Term apodization function.

b) The emission characteristics of the diode laser were studied under different conditions (temperature, current) using a FTIR Bruker IFS 120 HR spectrometer modified for emission experiments in the spectral ranges of 4200-4500 cm^{-1} in the case of the VCSEL GaSb and GaInAsSb/AlGaAsSb and diode. The beam of the laser diode was collimated and focused into the entrance aperture of the spectrometer using a on-off axis parabolic mirror and a CaF_2 lens. In all, 10 scans were co added with a resolution of 0.01 cm^{-1} and apodized by the Blackman-Harris 3-Term apodization function.

c) The lasers were used as a strong source of radiation and a high resolution FT spectrometer equipped in a sample chamber with an absorption cell was employed for sensitive and precise wavelength measurement. The amplitude of the drive current of the laser was modulated around its constant mean value. The frequency of modulation was set between 1 and 14 kHz. The glass cell (KBr windows) of length 26.5 cm and a diameter 5 cm, was filled up to 7 Torr pressure with methane or formaldehyde. The 50 scans of the spectrum were collected with a resolution of 0.01 cm^{-1}.

d) For a precise VCSEL GaSb laser line profile measurement an optical filter was applied in front of entrance aperture of the spectrometer (the transparency higher than 95 % in the range of 2.41-2.00 μm). All together 10 scans were co-added with a resolution of 0.1 cm^{-1} in the spectral region 2000-6000 cm^{-1}. High resolution non-apodized spectra (10 scans, resolution 0.0035 cm^{-1}) were collected in the spectral region 4150-4300 cm^{-1}.

2.4 Laser absorption spectroscopy

An absorption cell with a 26.5 cm long optical path was filled with methane, carbon monooxide or ammonia up to the maximum pressure 100 mbar. The laser emission was tuned from 4242 to 4231 cm^{-1} by changing of the injection current in the range from 3 mA to 13.5 mA with the step 5 μA and duration 0.2 s per step. The laser was stabilized at the constant temperature 293 K. The laser beam was focussed into the absorption cell using optical CaF_2 lens. The direct absorption spectrum was recorded by a photoconductor InSb detector working at the temperature of liquid nitrogen.

The signal from the detector was processed by a phase-sensitive amplifier (Stanford Research Systems SR530 Lock-in amplifier). The spectra were measured using mechanical modulation of the laser beam at a frequency of 400 Hz and collected by a computer.

3. RESULTS

3.1 MQW - GaInAsSb/AlGaAsSb diode laser-basic characteristics

FTIR spectroscopy was used to study the wavelength of the laser beam in relation to temperature and drive current. At a constant current (of 80 mA), the emission spectra were measured in the temperature range 273-323 K (see Figure 1). The GaInAsSb/AlGaAsSb laser acts monomodally throughout almost the whole range of the studied temperatures, with the exception of a narrow temperature interval between 290 and 294 K where the basic mode separates into a sequence of several small modes (approx. 3 cm^{-1} apart), and where the laser emits simultaneously at multiple wavelengths (4410-4430 cm^{-1}).

Value of the threshold current at room temperature is 40 mA. At a constant temperature, the laser can be tuned within a range of 5 cm^{-1} (the max. allowed current is 120 mA). If a combination of temperature and current changes is used, the laser can be tuned within a range of 10-20 cm^{-1}(see Figure 2). From the measured spectra we also calculated the laser tuning rates 0.602 cm^{-1}/K and 0.083 cm^{-1}/mA.

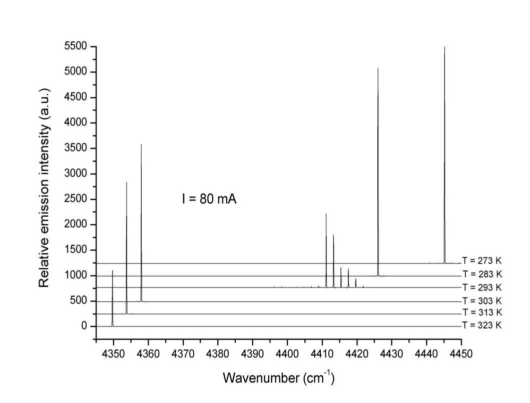

Figure 1: The relation of GaInAsSb/AlGaAsSb laser emission to temperature at a constant current of 80 mA (temperature step 10 K, 10 scans, resolution 0.01 cm^{-1}).

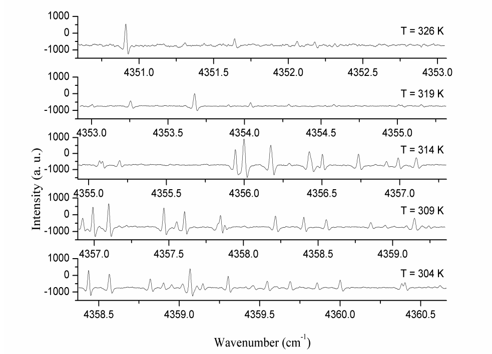

Figure 2: PA spectrum of formaldehyde diluted by nitrogen at a pressure of 55 Torr. Temperature of the diode laser was varied between 304 and 326 K.

3.2 Laser diode Fourier transform spectroscopy

The characterization of the lasers with the FT spectrometer led us to the idea of utilizing the laser emission as a potential high-energy-level source of radiation for the absorption FT spectroscopy purposes . For this reason, the amplitude of laser current was modulated by a sawtooth (positive or negative) waveform modulation around its mean value. Such a modulated beam was used for measurement of formaldehyde and methane spectra in the spectral range of the laser emission.

A series of parasite signals occurred in the FT spectrum obtained using the modulated beam. These were caused by the interference of the input modulated laser beam with the interferometer mirror movement. The position of these interferences varied in relation to the scanner velocity (the Bruker IFS 120 system has variable speed) and also to the modulation frequency of the diode laser.

Signal-to-noise ratio of the absorption spectrum (see Fig.5) improves at higher modulation frequencies. With a constant interferometer scanner velocity (40 kHz) and with a sufficiently high modulation frequency (above 10 kHz), (the laser current was modulated around its mean value symmetrically), the laser beam provides the interferometer with a sufficient amount of photons. Therefore, above 10 kHz there is no need to consider synchronization of the modulation frequency of the laser with the interferometer movement. At higher modulation frequencies, the laser acts as a quasi-continuous source, which may partially lead to the suppression of the parasite interferences. In our case, the maximal tested frequency of the diode modulation was 22.9 kHz, due to the laser current controller (Laser Photonic, model 5820) used. However, at the high modulation frequencies, the sawtooth leading edge became blunt and therefore a current non-linearity occurred in the minimum and maximum regions of the laser emission wavenumber. Due to this, the majority of the measurements were carried out at the modulation frequency of 10 kHz. In the case of the strong methane absorption in the 2.3 μm region of the GaInAsSb/AlGaAsSb laser, the 1 kHz laser modulation frequency was sufficient (see Figure 6) for reasonable signal-noise ratio.

Figure 6 depicts the spectra of methane obtained at different amplitudes of current modulation including a non-modulated beam. The maximum available amplitude, i.e. when the laser beam is modulated in the range of 57.5 mA to 146.5 mA allows us to cover a 7 cm^{-1} wide spectral range.

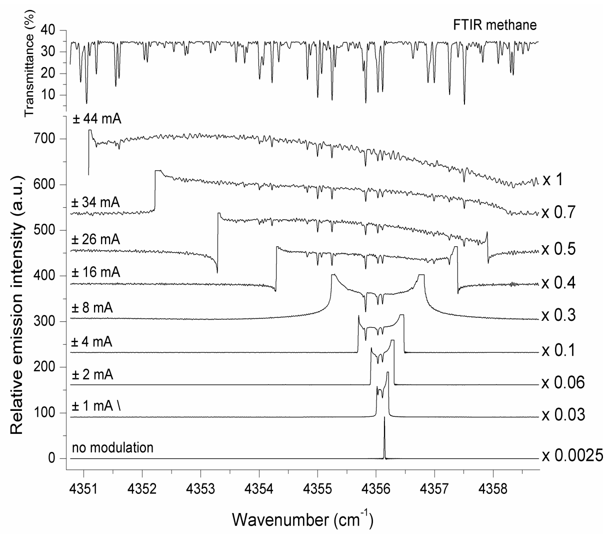

Figure 3: The spectrum of methane measured with a FTIR spectrometer in its absorption arrangement, using a 50 W halogen lamp (50 scans), compared to the spectra measured at different amplitudes of the modulation current. For a clearer view, the intensity of the individual spectra was divided by appropriate factors, as given in the figure (the mean current value 102.5 mA, modulation 1 kHz, 10 scans). Spectra are vertically shifted and multiplied by intensity factor.

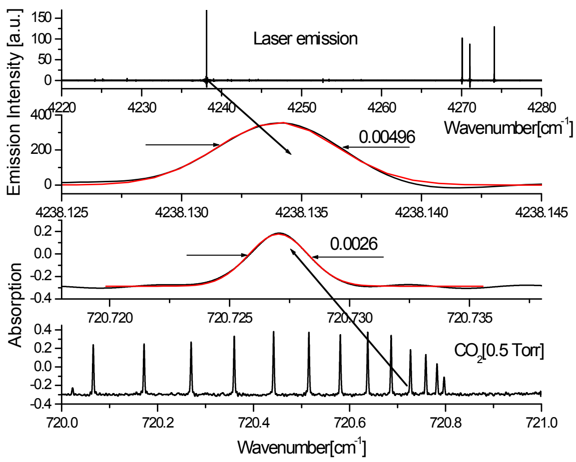

Figure 4: The emission from the most intense (4238 cm-1) laser line compared with the absorption line of CO_2 measured at the pressure 0.5 Torr with the resolution of 0.0035 cm^{-1}. The line profile was fitted with the Gauss function (the observed laser line width (FWHM) is 0.0049 cm^{-1}).

3.3 VCSEL diode laser-basic characteristics

VCSEL diodes suppose to emit the radiation in a single mode regime. Our investigation was primarily focused on the study of the modal characteristic of the individual lasers at the constant temperature and the constant injection current.

Laser No. A0012440

This laser works at the laboratory temperature with the output power about 60 µW with the maximal allowed value of injection current about 13.5 mA. The obtained threshold current values vary between 1.2 and 1.6 mA depending on the temperature (6^o – 40 °C). At the low injection current this laser works almost in a single mode regime (4230 cm^{-1}). At currents higher than 6 mA the laser starts to operate in a multi-modal regime. Figure 4 depicts the emission from the most intense (4238 cm^{-1}) laser line compared with the absorption line of CO_2 measured at the pressure 0.5 Torr with the resolution of 0.0035 cm^{-1}. The line profile was fitted with the Gauss function (the observed laser line width (FWHM) is 0.0049 cm^{-1}). Figure 5 depicts the laser emission at different temperatures for the constant injection current 8 mA.

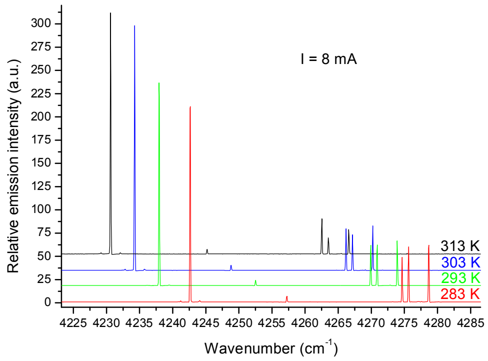

Figure 5: the GaSb laser emission - temperature step 10 K, injection current step 2 mA, 10 scans, resolution 0.1 cm-1.

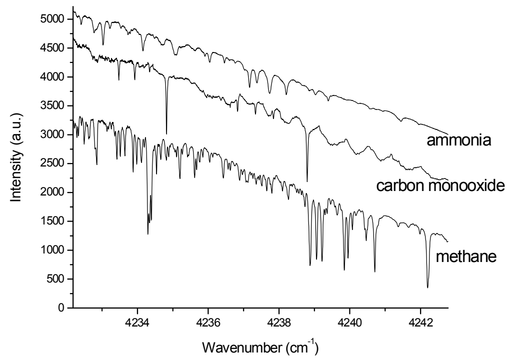

Figure 6: Absorption spectra of methane, carbon mono-oxide and ammonia at the pressure 100 mbar measured by VCSEL diode No. A001244093 K

3.4 Laser absorption spectroscopy

The main reason for the development of the VCSEL diodes is their potential application for the industrial trace gas monitoring. The structure of the lasers was designed for the spectral range of methane and carbon monoxide absorption. Figure 6 shows the comparison of three absorption spectra of NH_3, CO and CH_4 measured in a single 26.5 cm long optical path absorption cell at the pressure 100 mbar.

4. CONCLUSIONS

With the combination of the Fourier transform spectrometer and the MQW diode lasers as sources of coherent radiation, we compared the spectra measured with a FTIR spectrometer in its absorption arrangement using a 50 W halogen lamp, with a laser emission modulated by a current with different amplitudes. This technique proved to be very promising for the detection of weak absorption signals in a narrow spectral range of laser emission. We will further develop this technique, mainly with new types of lasers.

The main goal of the present work is the comparison of three new VCSEL diodes designed as the emission sources for the trace gas sensing (methane, carbon monooxide and ammonia) in the mid-infrared spectral range. The advantage of these GaSb based VCSEL diodes is their ability to emit radiation at the laboratory temperature and above (279 – 313 K) and the low threshold current values.

Our recent laboratory results demonstrate that most of the studied lasers are operating in a multi-modal regime. The laser processing methods are in the development.

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