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Multi-species Heterodyne Phase Sensitive Dispersion Spectroscopy over 80 nm using a MEMS-VCSEL

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ABSTRACT: Vertical cavity surface emitting lasers fabricated with movable microelectromechanical mirrors can offer continuous single-mode wavelength tuning up to 100 nm with high efficiency and in a very small package. Wide tunability makes these diode lasers ideally suited for multi-species and high-density gas analysis and the first demonstrations of direct absorption spectroscopy and wavelength modulation spectroscopy have already been published. The performance of these systems could nevertheless be enhanced by the use of the new molecular dispersion spectroscopic methods, as heterodyne phase sensitive dispersion spectroscopy. This technique bases its operation on the detection of the profile of the refractive index of the sample under analysis, in contrast to traditional architectures based on the measurement of optical absorption, and this provides noticeable advantages. First, the method is normalization-free and therefore the characteristic issue of the non-monotonic intensity profile during wavelength tuning of tunable vertical cavity surface emitting lasers is directly overcome. In addition, dispersion spectroscopy also provides an intrinsic linearity with concentration, high suitability for calibration-free operation, and an extended dynamic range, that are very desirable features to have in an optical gas analyzer. In this letter we present the first multi-species spectrometer based on a widely tunable vertical cavity surface emitting laser and heterodyne phase sensitive dispersion spectroscopy that is capable of operating in a tuning range of more of 80 nm for the simultaneous detection of several species.

Keywords: optical gas analysis, laser spectroscopy, molecular dispersion spectroscopy, wideband spectroscopy.

Vertical-cavity surface-emitting lasers (VCSELs) are a special kind of semiconductor diode lasers emitting light perpendicular to the wafer surface. The vertical resonator structure of VCSELs facilitates mass production in two-dimensional arrays and enables easy integration of photonic components such as microelectromechanical system (MEMS). The latter is particularly interesting for many applications as it enables fabrication of widely tunable laser sources commonly known as MEMS-VCSELs. MEMS-VCSELs offer mode-hop free broadband wavelength tunability with inherently longitudinal single-mode behavior. As a reference, whereas the monolithic structure of conventional VCSELs allows wavelength tuning of few nanometers [1], by changing the geometric length of the resonator with a movable MEMS mirror, wavelength ranges higher than 100 nm can be obtained [2,3]. This wide tuning capability of MEMS-VCSELs is, indeed, very attractive for multi-species gas analysis and indispensable for high-density gas spectroscopy. Nevertheless, when MEMS-VCSELs are employed in traditional absorption-based spectroscopic systems, many limitations arise from their non-monotonic intensity profile during wavelength tuning (produced by the distinctive features of the gain medium and the mirror) [4,5].This aspect of MEMS-VCSELs makes indispensable a thoroughly calibration process of the non-linear intensity profile of every particular device employed on the system. An alternative approach uses an additional reference intensity characterization sub-system, together with a model for the expected intensity transmitted through the sample [6,7]. Nevertheless, in both cases, the complexity of the instrument is increased and its operation becomes far more challenging. This issue can be, however, directly overcome by the use of new normalization-free molecular dispersion spectroscopic methods [8,9].

In this letter, we present, to the best of our knowledge, the first demonstration of a dispersion spectroscopy, Heterodyne phase sensitive dispersion spectroscopy (HPSDS) [8], set-up based on a MEMS-VCSEL. Operation is demonstrated over a tuning range of more than 80 nm for the simultaneous detection of hydrogen cyanide (HCN), acetylene (C_2H_2) and carbon monoxide (CO) followed by a brief discussion on the performance of the architecture.

METHODS

Brief introduction to HPSD Spectroscopy

The Kramers-Kronig relations show that both optical absorption and dispersion are associated to molecular resonances, being both a function of gas concentration [10]. Thus, by measuring either the wavelength-dependent absorption (traditional approach) or the wavelength-dependent dispersion (spectrum of the refractive index) of a gas sample, the concentration of any given analyte can be retrieved. Dispersion spectroscopy provides, nonetheless, additional advantages such as intrinsic linearity with concentration, extended dynamic range and high suitability for calibration-free operation [11,12]. However, the main focus of this manuscript is put on the fact that new dispersion spectroscopic methods are normalization-free [8], and hence the accuracy in the measurement of concentration is not affected by the wavelength-dependent nonlinear intensity profile of MEMS-VCSELs.

HPSDS is nowadays a well proven method that has already been validated in different adaptations and spectral ranges [8,13-15]. The basis of HPSDS is a three tone optical signal (generated by intensity-modulating the laser output) that is sent through the gas sample under analysis. In the proximity of spectral features (absorption lines) each optical tone encounters a slightly different value of refractive index, thus, the three signals will travel at dissimilar phase velocities and this induces optical phase shifts among them that can be measured and used to calculate the concentration of gas. More specifically, the phase shift at the center wavelength of the spectral line is directly proportional to the concentration of gas [13]. It is worthwhile to note at this point that, since the only parameter used for the estimation of concentration is the phase shift between optical signals, the actual power emitted by the laser has no effect on the output signal and, hence, it has no influence on the estimation of concentration (apart, of course, from its contribution to the signal to noise ratio of the measurement) [8]. Therefore, the output of the sensor will be independent from the intensity profile of the laser, not requiring any calibration process or for additional reference measurement paths.

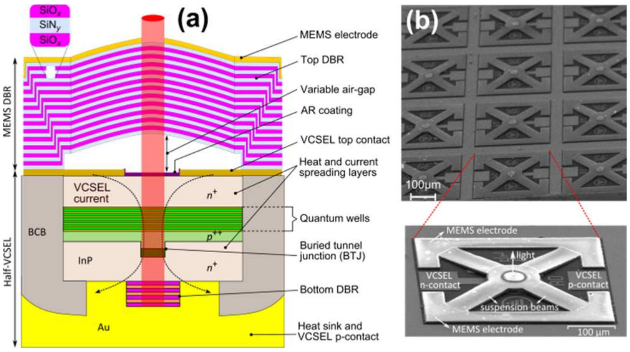
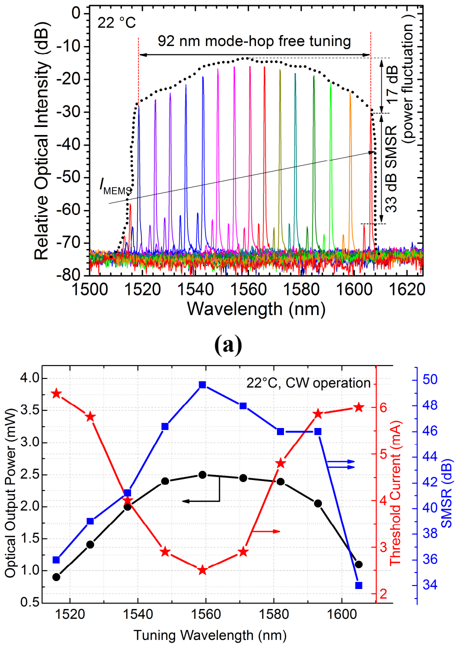


Fig. 1. (a) Schematic cross section of a MEMS-VCSEL.(b) SEM image of a 2-dimensional array of MEMS-VCSELs with a single device highlighted inset.

MEMS-VCSEL design, fabrication and characterization

A cross-section of a MEMS tunable VCSEL is shown in Fig.1(a). The device mainly consists of an AlInGaAs-based active region, two InP heat- and current-spreader layers, a buried tunnel junction (BTJ), a bottom distributed Bragg reflector (DBR) mirror and a top MEMS DBR. The circular BTJ with diameter, D_{BTJ} = 14 µm confines electrical current to guarantee a sufficiently high current density in the active region. The device is embedded in a gold-electroplated substrate. The combination of gold and dielectric bottom DBR enables a reflectivity of almost 100% over the entire tuning range. The concavely bent MEMS-DBR and planner active-VCSEL together construct an air-gap and result in a plane-concave resonator. By carefully incorporating a built-in stress within the MEMS SiN/SiO dielectrics, the concave bending is obtained. An optimal overlap between the gain profile and the fundamental mode enables a high amplification of that mode whereas higher order transversal modes experience a smaller overlap with the gain profile due to their different lateral intensity distribution. This ensures a high side-mode suppression ratio (SMSR). On top of the MEMS mirror, an actuation gold electrode is evaporated. The light coming through a circular opening in this gold electrode can be coupled to a standard lensed single-mode fiber. For an elaborated description of the design concept and fabrication technique, the reader is referred to [16,17]. The significantly short optical cavity length of the VCSEL is desirable for achieving a larger free spectral range (FSR), which is defined as the spectral separation between two adjacent longitudinal modes. For a properly designed MEMS-VCSEL, the FSR is the ultimate limit for mode-hop free tuning.

The wavelength can be swept by applying an actuation current I_{MEMS} through the MEMS electrode, as shown in 1(b). The dissipated heating power forces the MEMS DBR to go upwards and results in a red-shifting of the emission wavelength. The spectra for different control currents are shown in Fig. 2(a). The VCSEL starts lasing at 1514 nm for $I_{\mathrm{MEMS}} = 0$ mA. With an increasing current the lasing peak is continuously shifted and reaches up to 1606 nm at $I_{\mathrm{MEMS}} = 40$ mA, resulting in a mode-hop free single-mode tuning of 92 nm. The suppressed higher order transverse mode/modes can be seen at lower wavelength values adjacent to the lasing mode. The dotted line which refers to the continuous spectra of the tunable emission clearly shows a non-monotonic optical power profile with fluctuations of up to 17 dB from the center to the edge of the emitting band. The light-injection-current (*L-I*) characteristics of the laser at heat-sink temperature of 22 °C are also shown in Fig. 2(b). As can be seen, the threshold current, maximum output power and SMSR for different tuning wavelengths also change across the tuning range.



(a)

(b)

Fig. 2. (a) Tunable spectrum of the MEMS VCSEL. (b) Optical output power, threshold currents, and SMSR for different tuning wavelengths at 22°C.

At 1560 nm, the corresponding threshold current and the fiber coupled maximum optical power is 2.5 mA and 2.6 mW, respectively. As the gain maximum is set during manufacturing to the center wavelength; other wavelengths experience a lower gain. A similar behavior can be observed in the reflectivity of a MEMS-DBR. Moreover, a maximum reflectivity is achieved for both MEMS- and bottom DBR at the center wavelength due to design optimization. Both lower and higher wavelengths experience a lower reflectivity and thus higher cavity losses. The similar trend can be seen in the output power at different wavelengths. The fiber coupled optical power changes from 0.9 mW around the edges to 2.6 mW around the center of the emission range. As the gain decreases and losses increase the output power is reduced when moving away from the center wavelength. As also shown in Fig. 2(a), a minimum SMSR >33 dB across the tuning range is achieved.

Description of the set-up

The set-up of a HPSDS system (based on radio-frequency down-conversion heterodyning) using a MEMS-VCSEL is depicted in Fig. 3. Two low noise current sources supply the VCSEL and MEMS bias currents. For sweeping the emission wavelength, a triangular signal with 50% duty-cycle is connected to I_{MEMS} in series. The tunable emission from the laser is coupled to a lensed single-mode fiber (20 µm core diameter) and then intensity modulated (LN56S-FC, Thorlabs Inc., New Jersey, USA) at 1.5 GHz (matching the linewidth of the targeted spectral lines for CO and HCN) for the generation of the three tone HPSDS signal, which is then sent through the gaseous samples: HCN (740 Torr, 3.11 dB absorption at 1536 nm) and CO (740 Torr, 188 mdB absorption at 1568 nm), at ambient pressure, and C_2H_2 at a lower pressure (50 Torr, 8 dB absorption at 1530 nm); all from Wavelength References Inc., (Oregon, USA). The resulting optical signal is detected by a high-speed avalanche photodiode (~10 GHz bandwidth) the output of which is fed to a mixer (ZFM-11+, Mini-Circuits Inc., New York, USA) in order to down-convert the 1.5 GHz beat note to an intermediate frequency within the range of the lock-in amplifier (Signal Recovery 7265 Dual Phase DSP Lock-In Amplifier, 1 mHz to 250 kHz) employed. A second mixer (ZFM-11+, Mini-Circuits Inc., New York, USA) is used to extract the reference signal for the lock-in amplifier.

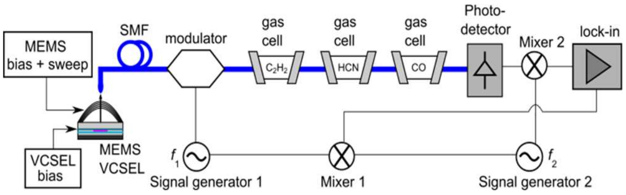


Fig. 3. Block diagram of the HPSDS system based on a MEMS-VCSEL.

RESULTS AND DISCUSSION

In the upper part of the inset on Fig. 4, the direct absorption spectrum (labeled as TLDAS) of the gas sample shows how, besides the parabolic intensity profile (clearly shown in Fig.2), there is an additional non-uniform ripple in the power emitted by the laser that makes baseline-removing very complicated when utilizing absorption-based methods (and even harder for wavelength modulation techniques). On the contrary, this ripple is completely inexistent on the actual HPSDS signal, which is shown in the lower part of the inset on Fig.4 (labeled as HPSDS). A not-properly balanced optical intensity modulator gives rise to a small baseline signal that can, nonetheless, be very easily fitted and removed by data processing. This issue, that would be negligible on a narrower wavelength range, could be completely removed by the use of a more appropriate modulator. The final HPSDS signal for a measurement spanning from 1516 nm to 1598nm (82nm) can be found in the main plot of Fig. 4, where complete rotational-vibrational spectra of CO, HCN and (except for a few lines) C_2H_2 are shown. The tuning time employed for the whole measurement is roughly 60 seconds (limited by the bandwidth of the output channels of the lock-in amplifier). For a rapid differentiation between different analytes, the envelope of the HPSDS signal for each gas has been highlighted in different colors (as said before, the troughs of the HPSDS spectrum provide a direct measure of concentration [13]). The zoom in area shows in more detail the HPSDS signal for the P14 ro-vibrational transition of HCN, the empty circles represent actual data points and the discontinuous line represents the expected results.

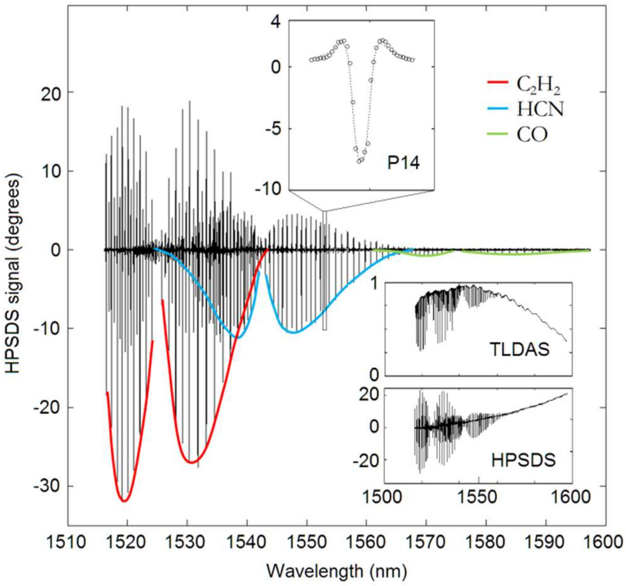


Fig. 4. HPSDS phase signal for whole spectral range. Inset: upper, direct absorption spectroscopy signal in arbitrary units, lower, HPSDS signal in degrees.

Regarding the main characteristic of the system, as it is the ability of analyzing several gases using a single laser source, the effect of a sample at a pressure different to which the system is optimized to operate has also been studied. As presented in the description of the set-up, the C_2H_2 cell has a pressure lower to that of the CO and HCN cells (making the linewidth of the acetylene resonances about one third of those from CO and HCN) and this induces a more symmetrical HPSDS signal (note the difference between the HPSDS signal for C_2H_2 and the signal for CO and HCN on Fig. 4). Nonetheless, we show how the capacity of the system for analyzing not only multiple species but also samples at different pressures remains intact (quantitatively, the much lower pressure on one of the cells employed in the experimental validation only reduces by a factor of 2 the limit of detection achievable exclusively for the given sample).

As a limitation, it must be added that, as a difference with common narrow tuning range diodes, the huge wavelength range swept by the MEMS-VCSEL put a lot of strain on the performance of the optical intensity modulator, being particularly important the stabilization of the temperature, the bias point and a good balance on the device.

It has been thus validated that it is possible to take advantage of the wide tuning range of MEMS-VCSELs for implementing a very simple dispersion spectrometer with the ability of detecting several analytes at different pressures into an optical span greater than 80 nm.

CONCLUSIONS

In this manuscript we present the first experimental validation of a HPSDS system based on a MEMS-VCSEL emitting in the near infrared. Operation is demonstrated over a tuning range of 82 nm for the simultaneous detection of multiple gases (hydrogen cyanide, acetylene and carbon monoxide) at different pressures.

The experiments performed show how HPSDS enables to take full advantage of MEMS-VCSELs for multi-species gas spectroscopy, by inherently overcoming all the problems associated to the non-monotonic intensity profile of these sources. The HPSDS-MEMS-VCSEL combination also endorses the system with other distinctive advantages, as an example, it provides the means for simple wavelength referencing. Because of the intrinsic linearity with concentration of HPSDS, when several samples (from the same or different gasses) are measured one after the other, the result is strictly equal to the sum of the individual contributions. Therefore, this allows sending an HPSDS interrogation signal through the sample that has been already propagated through a gas reference cell, being hence straightforward to retrieve the wavelength axis on detection. The HPSDS signal due to the sample under analysis (containing concentration information) can be later recovered by simply subtracting the calibrated or simulated wavelength reference spectrum. Beyond that, the wide tuning and the great number of lines analyzed open many new possibilities for obtaining an optimum accuracy in the estimation of concentration, as using the fitted envelope of the whole bands or multiline averaging approaches, instead of using single troughs of the HPSDS signal. These opportunities should ultimately improve accuracy and the limit of detection of the spectroscopic set-up.

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Notes

The authors declare no competing financial interest.

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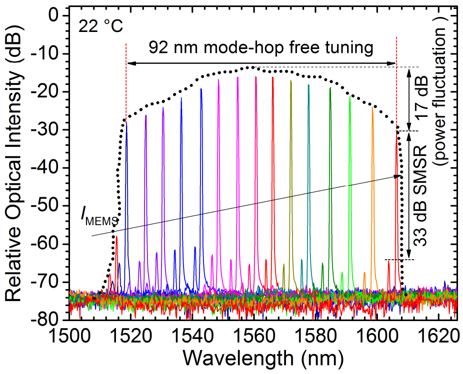

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We present the first experimental validation of a HPSDS system based on a MEMS-VCSEL emitting in the near infrared that, with a tuning range of 82 nm, enables the simultaneous detection of multiple species (hydrogen cyanide, acetylene and carbon monoxide) at different pressures. This results in a compact, cost efficient and flexible set-up that could provide new advantages to the field optical gas detection and analysis.