Surface emitting ring quantum cascade lasers for chemical sensing

Rolf Szedlak
Jakob Hayden
Pedro Martín-Mateos
Martin Holzbauer
Andreas Harrer
Benedikt Schwarz
Borislav Hinkov
Donald MacFarland
Tobias Zederbauer
Hermann Detz
Aaron Maxwell Andrews
Werner Schrenk
Pablo Acedo
Bernhard Lendl
Gottfried Strasser
Surface emitting ring quantum cascade lasers for chemical sensing

Rolf Szedlak,a,* Jakob Hayden,b Pedro Martín-Mateos,c Martin Holzbauer,a Andreas Harrer,a Benedikt Schwarz,a Borislav Hinkov,a Donald MacFarland,a Tobias Zederbauer,a Hermann Detz,d Aaron Maxwell Andrews,a Werner Schrenk,a Pablo Acedo,c Bernhard Lendl,b and Gottfried Strasser,a

aTU Wien, Institute of Solid State Electronics, Center for Micro- and Nanostructures, Vienna, Austria
bTU Wien, Institute of Chemical Technologies and Analytics, Vienna, Austria
cUniversidad Carlos III de Madrid, Departamento de Tecnología Electrónica, Leganés, Madrid, Spain
dAustrian Academy of Sciences, Vienna, Austria

Abstract. We review recent advances in chemical sensing applications based on surface emitting ring quantum cascade lasers (QCLs). Such lasers can be implemented in monolithically integrated on-chip laser/detector devices forming compact gas sensors, which are based on direct absorption spectroscopy according to the Beer–Lambert law. Furthermore, we present experimental results on radio frequency modulation up to 150 MHz of surface emitting ring QCLs. This technique provides detailed insight into the modulation characteristics of such lasers. The gained knowledge facilitates the utilization of ring QCLs in combination with spectroscopic techniques, such as heterodyne phase-sensitive dispersion spectroscopy for gas detection and analysis.

© The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction in any form is by permission of SPIE. Unauthorized reproduction of the article electronically or otherwise will be prosecuted. [DOI: 10.1117/1.OE.57.1.011005]

Keywords: quantum cascade laser; quantum cascade detector; gas sensing; radio frequency modulation; heterodyne phase-sensitive dispersion spectroscopy.

Paper 170836SS received Jun. 2, 2017; accepted for publication Aug. 9, 2017; published online Sep. 1, 2017.

1 Introduction

The midinfrared spectral region exhibits numerous ro-vibrational absorption lines of various substances. Therefore, light sources emitting in this wavelength range are desirable tools for sensing and chemical fingerprinting. Due to their compact size, tailorable emission characteristics,1,2 and high spectral brightness,3 quantum cascade lasers (QCLs)4 are commonly used for such absorption experiments.5 Surface emitting QCLs possess considerable advantages compared with their edge emitting counterparts. They facilitate on-chip testing and two-dimensional array integration. Due to their rather large emission aperture, these lasers can produce narrow beam profiles.6 The first surface emitting QCL1 was demonstrated utilizing a second-order distributed-feedback (DFB) grating. Subsequently, further approaches have been successfully implemented: in photonic crystals8,9 artificial periodic structures provide optical feedback and generate light beams in vertical direction. With random lasers10,11 almost diffraction limited broadband surface emission can be achieved, while losing tunability. Manipulating beam characteristics through wave engineering has been demonstrated with vertically emitting circular DFB gratings12 as well as graded photonic heterostructures.13

Surface emitting ring QCLs14 typically consist of a circular ring waveguide with a second-order DFB grating. The latter provides single-mode selection as well as vertical light emission while the circular ring geometry creates a collimated and rotationally symmetric far field. This desirable beam profile can be modified by well-directed manipulation of a regular DFB grating.15 Single-mode emission and continuous-wave operation at room temperature16,17 in combination with the collimated emission beam make ring QCLs suitable tools for chemical sensing applications.18,19 Due to their compact size and small footprint, these lasers are ideal light sources for the application in miniaturized sensing setups, such as substrate-integrated hollow waveguides.20

2 Surface Emitting/Detecting On-Chip Sensor

Typical state-of-the-art applications make use of conventional sensing setups, which include a light source, a light–analyte interaction region, and an external separate detector, e.g., based on the mercury-cadmium-telluride (MCT) material system. Utilization of a quantum cascade detector (QCD)21,22 in combination with a separate QCL mounted on an individual chip demonstrates the capabilities of quantum cascade technology in spectroscopy.23 The development of bifunctional quantum cascade heterostructures24 enables the realization of monolithically integrated lasers (QCL) and detectors (QCD) fabricated on the same chip. Edge emitting and detecting bifunctional devices have successfully been used for sensing of liquids.25 However, the limited length of the interaction region between laser and detector makes gas sensing impractical. One possible solution is to guide the light on the chip and thereby increase the interaction length.26 Certainly, this approach is also limited in terms of absorption path length due to restrictions in on-chip mode guiding.

In contrast, utilization of surface emitting and detecting quantum cascade structures fabricated on the same chip in combination with an external light–analyte interaction region provides, in theory, arbitrarily long absorption paths and facilitates remote sensing experiments.27,28 Furthermore,
the small footprint of such sensors enables the realization of compact sensing systems. Figure 1(a) shows a scanning electron microscope (SEM) image of a surface emitting ring QCL with a surface detecting disk QCD in its center. Vertical light emission and detection are provided by the second-order DFB grating (QCL) and the metal hole grating (QCD), respectively. A sketch of the corresponding sensing setup is shown in Fig. 2(a).

Light emitted from the ring QCL is collimated by a lens and modulated by a chopper in order to filter out the high-frequency electrical cross talk before it propagates through the gas cell. A flat gold mirror at the end of the cell reflects the light back toward the chip. After inverse propagation along its initial path, the light is focused onto the sensor chip where it is detected by the disk QCD. In this setup, an image of the laser source is projected back onto the sensor chip where it is detected by the disk QCD. In this setup, an image of the laser source is projected back onto the sensor chip, and is back-reflected by a flat gold mirror. Both concepts, with the disk and ring detector, are based on conventional absorption spectroscopy according to the Beer–Lambert law.

3 Modulation Characteristics and Dispersion Spectroscopy

In contrast, ring QCLs can also be used in combination with sophisticated spectroscopic techniques. Knowledge of the laser’s current-tuning characteristics is important for a variety of sensing techniques, such as wavelength- and frequency-modulation spectroscopy, intrapulse absorption spectroscopy, chirped laser dispersion spectroscopy, and heterodyne phase-sensitive dispersion spectroscopy (HPSDS). The latter is a molecular dispersion technique that probes a sample’s refractive index spectrum, rather than its absorption, via the phase of radio frequency-modulated laser light. Its sensitivity to the signal’s phase makes
HPSDS immune to power fluctuations and therefore enables calibration-free sensor operation.

In the following, an HPSDS spectrometer is implemented and experimentally validated. Therefore, a surface emitting single-mode ring QCL [Fig. 3(a)] is sinusoidally modulated at radio frequencies and swept across a well-known absorption line. This technique allows a thorough investigation of the laser’s modulation characteristics. A detailed description of the quantum cascade heterostructure can be found in Ref. 37. In this study, characteristic laser tuning parameters are fitted to a known sample’s absorption profile using the model described in Ref. 38. Based on this characterization, HPSDS gas sensing experiments are performed.

The ring laser is operated at liquid nitrogen temperatures, and its emitted radiation is measured with an MCT detector after passing through a 10-cm-long gas cell filled with 0.4% CH₄ in N₂ at a pressure of 24 mbar. A sketch of the corresponding setup is shown in Fig. 3(b). Different modulation frequencies between 1 and 150 MHz are utilized in combination with four DC current values (65, 101, 150, and 200 mA). The corresponding laser submount temperatures (118, 110, 100, and 88 K) are reduced in order to stabilize the emission wavelength of the laser. All operating points are well above threshold, which is found to be at 27 mA (80 K) and at 43 mA (110 K). For each DC current, the laser is slowly tuned over the two absorption features at 1322.08/cm and 1322.15/cm. The tuning frequency of the current ramp is around 50 MHz with a peak-to-peak amplitude of 11.8 mA. Subsequently, the signal of the MCT is fed into a mixer and downmixed to 100 kHz in order to measure the amplitude and phase with a lock-in amplifier. Figure 4 shows the amplitude (a) and phase (b) of the downmixed signal at a modulation frequency of 100 MHz and a DC current of 200 mA. For all DC currents and modulation frequencies, only the larger feature at 1322.08/cm is fitted and used for the following analysis.

According to the notation in Ref. 38, Fig. 5(a) shows the ratio \( \Delta f/m = \Delta f/(\Delta P/P_0) \) between absolute frequency modulation (FM) and intensity modulation (IM) index. In Fig. 5(b), the FM–IM phase shift \( \Theta \) is provided as a function of the modulation frequency. The region between 30 and 150 MHz is characterized by a rather flat behavior of \( \Delta f/m \) and \( \Theta \). However, below 20 MHz, the rise of the
FM–IM ratio and phase indicates the onset of thermal tuning, which is a figure of merit in ring QCLs. Based on these tuning characteristics, HPSDS gas sensing measurements were performed using a different absorption line of CH$_4$. The laser characterization confirmed that a low bias current and a high modulation frequency are beneficial for HPSDS. On the other hand, a large optical intensity is advantageous for a high signal-to-noise ratio. Operating the laser at a DC current of 92 mA (120 K) and 183.5 mA (100 K) with a modulation frequency of 150 MHz, different gas concentrations are investigated. Figure 6 shows the corresponding normalized phase in a concentration range from 1,000 to 12,500 ppm. The different linear ranges for the two bias current setpoints are clearly visible. This can be attributed to the different FM/IM indices for the two setpoints [compare Fig. 5(a)]. The low bias current setpoint corresponds to a predominantly amplitude modulated case (small FM/IM index), yielding a large dynamic range, while a high bias current favors frequency modulation and gives larger phase shifts at the expense of limited linearity. The extracted 3σ limit of detection, defined as the noise-equivalent concentration, for DC currents of 92 and 183.5 mA is extrapolated from gas measurements with low peak absorption and amounts to 16 and 2 ppm, respectively. The noise floor σ is measured with no CH$_4$ in the gas cell.

4 Conclusion

We present recent advances in the field of ring QCLs for chemical sensing applications. These light sources have been implemented in monolithically integrated on-chip laser/detector devices for gas sensing. Prototype devices featuring a disk and a ring detector have been realized. The latter enables mutual commutation between laser and detector. Furthermore, an introductive characterization of the radio frequency modulation characteristics up to 150 MHz of surface emitting ring QCLs is demonstrated. This knowledge paves the way for an implementation of these compact and versatile midinfrared light sources in gas sensing applications exploiting efficient spectroscopic techniques, such as HPSDS.

Disclosures

The authors declare no competing financial interest.

Acknowledgments

The authors acknowledge the support by the Austrian Science Fund (FWF) Project No. F 49 (Next-Lite). J.H. and B.L. acknowledge the financial support received from the Competence Center Austrian Smart Systems Integration Research Center as part of the Austrian Competence Centers for Excellent Technologies program. B.S. acknowledges the support from the FWF Project No. P 28914. H.D. acknowledges the support through an APART fellowship from the Austrian Academy of Sciences.

References

1. G. Wysocki et al., “Widely tunable mode-hop free external cavity quantum cascade laser for high resolution spectroscopic applications,” Appl. Phys. B 81(6), 769–777 (2005).
2. B. G. Lee et al., “Widely tunable single-mode quantum cascade laser source for mid-infrared spectroscopy,” Appl. Phys. Lett. 91(23), 231101 (2007).
3. B. Hinkov et al., “Quantum cascade laser in a master oscillator power amplifier configuration with watt-level optical output power,” Opt. Express 21, 19180–19186 (2013).
4. J. Faist et al., “Quantum cascade laser,” Science 264(5158), 553–556 (1994).
5. A. A. Kosterev and F. K. Tittel, “Chemical sensors based on quantum cascade lasers,” IEEE J. Quantum Electron. 38, 582–591 (2002).
6. M. Schubert and F. Rana, “Analysis of terahertz surface emitting quantum-cascade lasers,” IEEE J. Quantum Electron. 42, 257–265 (2006).
7. D. Hofstetter et al., “Surface-emitting 10.1 μm quantum-cascade distributed feedback lasers,” Appl. Phys. Lett. 75(24), 3769–3771 (1999).
8. R. Colombelli et al., “Quantum cascade surface-emitting photonic crystal laser,” Science 302(5649), 1374–1377 (2003).
9. M. S. Vitiello et al., “Photonic quasi-crystal terahertz lasers,” Nat. Commun. 5, 5884–5891 (2014).
10. S. Schönhuber et al., “Random lasers for broadband directional emission,” Optica 3, 1035–1038 (2016).
11. R. Szedlak et al., “The influence of whispering gallery modes on the far field of ring lasers,” Sci. Rep. 6, 19325–19331 (2016).
12. G. Xu et al., “Efficient power extraction in surface-emitting semiconductor lasers using graded photonic heterostructures,” Nat. Commun. 3, 952–958 (2012).
13. E. Mujagic et al., “Efficient power extraction in surface-emitting semiconductor lasers using graded photonic heterostructures,” Nat. Commun. 3, 952–958 (2012).
14. R. Szedlak et al., “Low divergence single-mode surface emitting quantum cascade ring lasers,” Appl. Phys. Lett. 93(16), 161101 (2008).
15. R. Szedlak et al., “Remote sensing with commutable monolithic laser and detector,” ACS Photonics 3(10), 1794–1798 (2016).
16. B. Hinkov et al., “RF-modulation of mid-infrared distributed feedback quantum cascade lasers,” Opt. Express 24, 3294–3312 (2016).
17. P. Kluczynski et al., “Wavelength modulation absorption spectrometry – an extensive scrutiny of the generation of signals,” Spectrochim. Acta Part B 56(8), 1277–1354 (2001).
18. S. Bozzi et al., “Frequency modulation spectroscopy by means of quantum-cascade lasers,” Appl. Phys. B 85(2), 223–229 (2006).
19. C. Reidl-Leuthner and B. Lendl, “Toward stand-off open-path measurements of NO and NO2 in the sub-parts per million meter range using quantum cascade lasers (QCLs) in the intra-pulse absorption mode,” Appl. Spectrosc. 67, 1368–1375 (2013).
20. A. Hangauer et al., “Chirped laser dispersion spectroscopy using a directly modulated quantum cascade laser,” Appl. Phys. Lett. 103(19), 191107 (2013).
21. P. Martín-Mateos and P. Acedo, “Heterodyne phase-sensitive detection for calibration-free molecular dispersion spectroscopy,” Opt. Express 22, 15143–15153 (2014).
22. P. Martín-Mateos et al., “Heterodyne phase-sensitive dispersion spectroscopy in the mid-infrared with a quantum cascade laser,” Anal. Chem. 89(11), 5916–5922 (2017).
23. J. Hayden et al., “A quantitative comparison of dispersion- and absorption-spectroscopic gas sensing,” Proc. SPIE 10110, 101100Z (2017).
24. A. Hangauer et al., “High frequency modulation capabilities and quasi single-sideband emission from a quantum cascade laser,” Opt. Express 22, 23439–23455 (2014).

Biographies for the authors are not available.