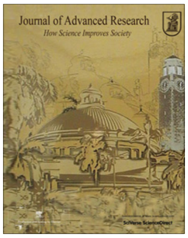
Journal of Advanced Research (2015) **6**, 529–533

Cairo University

Journal of Advanced Research



LETTER TO THE EDITOR

Mid-infrared laser-spectroscopic sensing of chemical species

Markus W. Sigrist

ETH Zürich, Institute for Quantum Electronics, Laser Spectroscopy and Sensing Laboratory, Otto-Stern-Weg 1, CH-8093 Zürich, Switzerland

ARTICLE INFO

Article history:
Received 5 August 2014
Received in revised form 23 September 2014
Accepted 29 September 2014
Available online 13 October 2014

Keywords:
Mid-IR lasers
Spectroscopy
Gas sensing
Surgical smoke
Glucose

ABSTRACT

This letter reports on mid-infrared laser-based detection and analysis of chemical species. Emphasis is put on broadly tunable laser sources and sensitive detection schemes. Selected examples from our lab illustrate the performance and potential of such systems in various areas including environmental and medical sensing.

Introduction

In the recent years spectroscopic schemes have made significant progress thanks to new developments in lasers and detection techniques. Today, laser-based sensing of chemical species offers high sensitivity and specificity, large dynamic range, multi-component capability, and lack of pretreatment or preconcentration. The availability of broadly tunable mid-infrared sources – particularly in the important 3–4 μm wavelength range – such as quantum cascade lasers (QCLs) [1–4], tunable radiation generated by nonlinear optical processes such as difference frequency generation (DFG) [5,6] and optical parametric oscillators (OPOs) [5,7,8], interband cascade diode lasers (ICLs) [9–11], distributed feedback (DFB) diode lasers [12,13], or the most recent development of diode-pumped lead salt vertical external cavity surface emitting lasers (VECSELs) [14,15] has certainly eased the implementation of laser-based sensing devices.

Furthermore, detection schemes such as multipass absorption, cavity-enhanced and cavity-ringdown or photoacoustic detection are by now well-established techniques so that their implementation has become straightforward.

In the last years we have developed laser-spectroscopic systems in our laboratory for various applications in different areas ranging from environmental and industrial to medical and forensic fields. The description of some selected examples illustrates the performance and potential of laser spectroscopic sensing.

E-mail address: sigristm@phys.ethz.ch

Peer review under responsibility of Cairo University.

ELSEVIER **Production and hosting by Elsevier**

http://dx.doi.org/10.1016/j.jare.2014.09.002

Trace gas detection

The first example concerns environmental gas sensing. Some time ago we implemented a photoacoustic system consisting of two line-tunable CO_2 lasers ($^{12}CO_2$ and $^{13}CO_2$) covering the spectral range between 9.2 and 11.4 μm and a home-made multipass resonant photoacoustic cell equipped with 16 microphones for signal enhancement.

The entire system is fully automated and built in a mobile trailer and has been used unattended for extended periods of time (see Fig. 1). As example, one-week concentration profiles of ethene (C_2H_4), ammonia (NH_3) and CO_2 have been recorded in 1-min intervals at the roadside location at the exit of a street tunnel to evaluate street traffic emissions [16]. This was achieved by automatic switching between different laser transitions of the two lasers that are characteristic for strong absorption of these gases yet avoiding spectral interferences. Regularly, the modulation frequency of the chopper switched to a (strongly) absorbing water line to check its matching with the acoustic resonance frequency of the cell. As a result, the concentration profiles followed the traffic density and reached rather high maximum values of 2000 ppm for CO_2, 400 ppb for ethene and up to 600 ppb for ammonia. These data were used to evaluate mean emission data of 200 g km^{-1} $vehicle^{-1}$ for CO_2, 26 mg km^{-1} $vehicle^{-1}$ for ethene and 31 mg km^{-1} $vehicle^{-1}$ (for LDV: low-duty vehicles) or 14 mg km^{-1} $vehicle^{-1}$ (for HDV: high-duty vehicles) for ammonia. Obviously, one would strongly miniaturize such a system today by replacing the CO_2 lasers with modern semiconductor lasers.

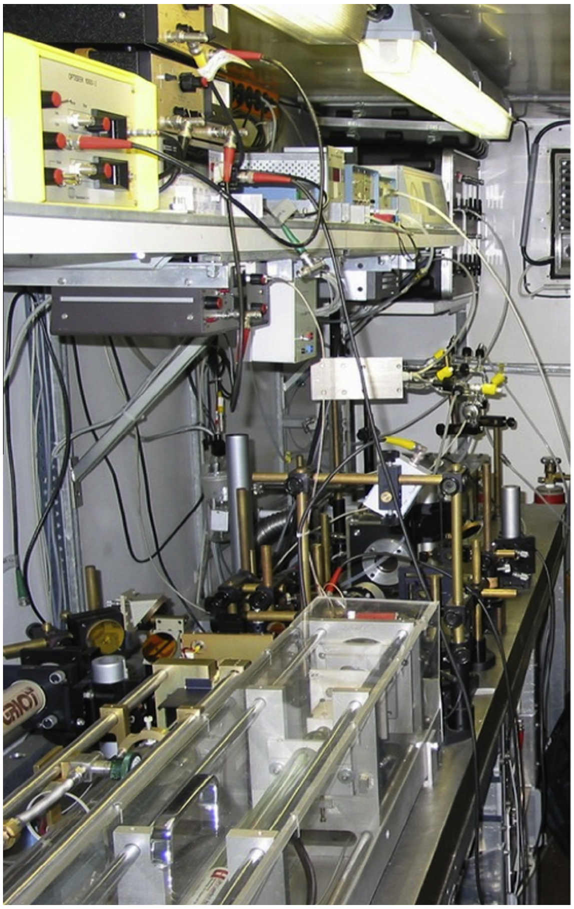


Fig. 1 Inside of automated mobile CO_2-laser photoacoustic system for field monitoring of air pollutants: lower left: sealed-off $^{12}CO_2$- and $^{13}CO_2$ lasers side by side and home-built photoacoustic cell in the back.

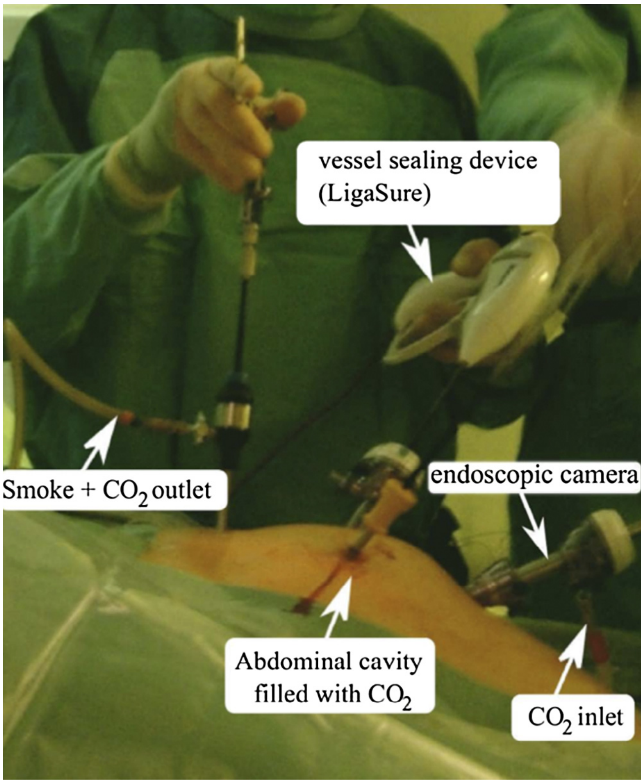


Fig. 2 Image of operation theater in the University Hospital Zurich during minimal invasive surgery with electroknife (LigaSure). Collection of smoke and CO_2 in Tedlar bags for subsequent laser-spectroscopic analysis in our lab.

A second example concerns first measurements with a novel lead-salt VECSEL (vertical extended cavity surface emitting laser). The VECSEL is pumped with a near-IR diode laser and tuning is performed by simply applying a voltage ramp (0–100 V) on the VECSEL piezo element. The main features are a broad and fast tuning, e.g., between 2950 cm^{-1} and 3100 cm^{-1} within 2 s. This wavelength range is of special interest in petrochemical industry and other areas for monitoring, e.g., C_1–C_4 alkanes (i.e., methane, ethane, propane and butanes) in gas mixtures. With this laser source and a simple multipass absorption cell we achieved sub-ppm detection limits for all these hydrocarbons in mixtures even in the presence of a high water vapor content.

Analysis of surgical smoke

A further example of gas sensing concerns a medical application, namely the analysis of surgical smoke that is produced during minimal-invasive surgery with an electro-knife [17,18]. This study was done in collaboration with the University hospital in Zurich. There is an ongoing controversial discussion on compounds present in the smoke that could be potentially hazardous for the medical personnel and/or the patient. Since

Table 1 Detected chemical compounds in the 31 measured samples of surgical smoke. Listed are seven substances with their concentrations in ppm. LOD: limit of detection, REL: recommended exposure limit.

Substance	No. of samples	Median concentration	Range of concentrations	LOD (ppm)	REL (ppm)
Carbon monoxide (CO)	6	0.85	< 0.25–3.20	0.25	30
Hydrogen fluoride (HF)	6	< 0.00011	< 0.00011	0.00011	1
Sevoflurane ($C_4H_3F_7O$)	27	110	< 20–450	20	2[a]
Methane (CH_4)	27	0.39	< 0.1–34.0	0.1	10^4
Ethane (C_2H_6)	27	< 0.1	< 0.1–2.0	0.1	10^4
Ethylene (C_2H_4)	27	< 5	< 5–10	5	10^4
Water vapor (H_2O), abs.	27	0.61%	0.27–1.1%	–	–

[a] No REL value for Switzerland. The US Institute for Occupational Safety and Health recommends exposure limits of 2 ppm for all halogenated anesthetics.

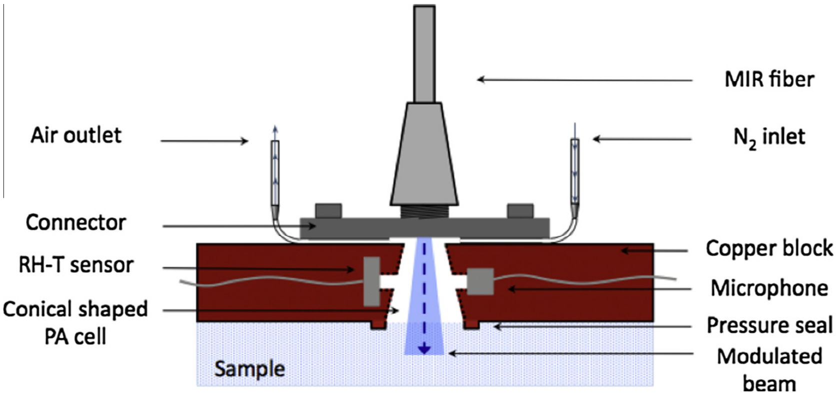


Fig. 3 Homebuilt IR-fiber-coupled photoacoustic cell for non-invasive glucose measurements. See text for details.

most previous studies were performed *in vitro*, we made the first *in vivo* experiments with laser spectroscopy on smoke samples that we collected in Tedlar bags during the course of several operations (see Fig. 2). We recorded infrared spectra of the samples with a home-made broadly tunable DFG system [19] in our laboratory with the exception of CO recording which was performed with a diode-laser-based system [17]. The spectral analysis was then performed with a principal component analysis [20]. Besides water vapor, mainly traces of methane, ethane, ethylene, and – surprisingly high concentrations of up to 450 ppm – of the anesthetic gas sevoflurane were found in varying concentrations. As listed in Table 1 all concentrations with the exception of sevoflurane were below recommended exposure limits [18].

Toward non-invasive *in vivo* glucose sensing

With some 600 million patients worldwide, Diabetes mellitus is a widespread human metabolic disease. Since currently no treatment exists, the therapy consists in monitoring the blood glucose concentration of a patient and adjusting it to near-normal levels of 60–120 mg/dl. This implies measurements of the blood glucose level several times a day which is rather uncomfortable. Since no non-invasive method exists up to now despite intense research with numerous techniques, the measurement still involves finger pricking to take small blood samples. We made some first steps toward the goal of non-invasive glucose monitoring by developing a new scheme based on mid-infrared laser photoacoustic spectroscopy. As laser source we used an external cavity quantum cascade laser (EC-QCL) tunable in the range around 1000 cm^{-1} where glucose exhibits two strong absorption peaks (at 1034 cm^{-1} and 1080 cm^{-1}). The main problem of the mid-IR range is the strong water absorption in the tissue. This limits the penetration depth through skin to approximately 50 μm, i.e. blood vessels cannot be reached but instead the interstitial fluid within the epidermis whose glucose level is related to the blood glucose level with some time delay of 10–30 min can be accessed. We developed a new fiber-coupled photoacoustic (PA) cell which is directly brought into contact with the sample, e.g. the skin at the human forearm [21]. Fig. 3 depicts the details of the PA cell with the mid-IR fiber (AgClBr) inlet, the small air volume of only 35 mm^3 for detecting the PA signal with an electret microphone, a relative humidity and temperature (RH-T) sensor and a dry air or N_2 flow to keep the humidity in the air chamber low.

We performed numerous measurements on various samples: aqueous solutions of glucose [22], solutions of keratinocytes (skin cells), epidermal skin samples [23] and *in vivo* human skin. By setting the QCL to the 1034 cm^{-1} glucose absorption peak we recorded the PA signal for various glucose concentrations for determining limit of detection (LOD). We achieved an LOD of 30 mg/dl (for SNR = 1) for aqueous glucose solutions, and an LOD of 50 mg/dl (SNR = 1) for keratinocytes solutions. By placing epidermal skin samples in direct contact with aqueous glucose solutions we were able to monitor the time-resolved diffusion of glucose into the skin sample (LOD = 100 mg/dl (SNR = 1)) [23]. Finally we monitored the PA signal as a function of time during an oral glucose tolerance test (OGTT) *in vivo* by placing the PA cell in direct contact with the human forearm of volunteers. Our preliminary results look promising although some main issues such as remaining instabilities of the PA measurements and the limited detection sensitivity which is close to expected glucose concentration changes during an OGTT need yet to be addressed.

An alternative method for investigating strongly scattering samples such as tissue could be a novel technique that we developed named Photothermal Diffuse Reflection (PTDR) Spectroscopy [24]. This method combines the advantages of the selective strong absorption in the mid-infrared with the excellent detection sensitivity in the near-infrared in a non-contact configuration.

Conclusions

Laser-spectroscopic techniques offer unique possibilities for monitoring chemical species which is demonstrated with examples from multi-component gas sensing in environmental or medical applications such as urban air monitoring or surgical smoke analysis. In both cases a narrowband broadly tunable IR laser is essential for achieving high selectivity down to the sub-ppb concentration range. On the other hand, a novel approach with a QCL-based photoacoustic sensor toward non-invasive glucose monitoring through human skin is presented. First *in vivo* tests appear promising but further research and development is definitely needed to actually demonstrate the feasibility of this method.

A vast literature is available on laser-based chemical sensing. This short summary of own projects is just meant to illustrate some main features and possibilities but also limitations of this technique. The main issue remains the availability of appropriate broadly tunable laser sources and sensitive detection schemes. Hence, the development of new laser types enables new possibilities, e.g., more field capabilities in ambient and industrial monitoring or point-of-care instrumentation in medical applications. It can also be foreseen that new areas of application for laser-based sensors will open up.

Conflict of interest

The author has declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

Acknowledgements

The author thank his coworkers D. Marinov, M. Gianella, J. Rey and J. Kottmann for their valuable contributions as well as Dr. D. Hahnloser (University Hospital Zurich) for the fruitful collaboration within the frame of the surgical smoke project and Drs. J. Luginbühl and E. Reichmann (Children Hospital Zurich) for providing keratinocyte solutions and epidermal skin samples for the glucose Project. Funding by the Swiss National Science Foundation, ETH Zurich and Glucometrix is greatly acknowledged.

References

[1] Riedi S, Hugi A, Bismuto A, Beck M, Faist J. Broad band external cavity tuning in the 3–4 μm window. Appl Phys Lett 2013;103:031108.

[2] Rao GN, Karpf A. External cavity tunable quantum cascade lasers and their applications to trace gas monitoring. Appl Opt 2011;50:A100–15.

[3] Reyes-Reyes A, Hou Z, van Mastrigt E, Horsten RC, de Jongste JC, Pijnenburg MW, et al. Multicomponent gas analysis using broadband quantum cascade laser spectroscopy. Opt Express 2014;22:18299.

[4] Bandyopadhyay N, Bai Y, Tsao S, Nida S, Slivken S, Razeghi M. Room temperature continuous wave operation of $\lambda \sim 3$–3.2 μm quantum cascade lasers. Appl Phys Lett 2012;101: 241110.

[5] Sorokina IT, Vodopyanov KL, editors. Solid-state mid-infrared laser sources. Topics in applied physics. Berlin Heidelberg: Springer; 2003. p. 89.

[6] Sigrist MW, Wächter H, Gianella M. Generation of coherent mid-infrared radiation by difference-frequency mixing. In: Träger F, editor. Springer handbook of lasers and optics. Berlin Heidelberg: Springer; 2012 [chapter 11.10].

[7] Borsutzky A, L'Huillier JA. Optical parametric oscillators. In: Träger F, editor. Springer handbook of lasers and optics. Berlin Heidelberg: Springer; 2012 [chapter 11.9].

[8] Arslanov DD, Spunei M, Mandon J, Cristescu SM, Persijn ST, Harren FJM. Continuous-wave optical parametric oscillator based infrared spectroscopy for sensitive molecular gas sensing. Laser Photonics Rev 2013;7:188–206.

[9] Bewley WW, Canedy CL, Kim CS, Kim M, Merritt CD, Abell J, et al. High-power room-temperature continuous-wave mid-infrared interband cascade lasers. Opt Express 2012;20: 20894.

[10] Bauer A, Dallner M, Kamp M, Höfling S, Worschech L, Forchel A. Shortened injection interband cascade lasers for 3.3–3.6 μm-emission. Opt Eng 2010;49:111117.

[11] Kim M, Canedy CL, Bewley WW, Kim CS, Lindle JR, Abell J, et al. Interband cascade laser emitting at in continuous wave above room temperature. Appl Phys Lett 2008;92:191110.

[12] Naehle L, Belahsene S, von Edlinger M, Fischer M, Boissier G, Grech P, et al. Continuous-wave operation of type I quantum well DFB laser diodes emitting in the 3.4 μm wavelength range around room temperature. Electron Lett 2011;47:46–7.

[13] Krzempek K, Lewicki R, Nähle L, Fischer M, Koeth J, Belahsene S, et al. Continuous wave distributed feedback diode laser-based sensor for trace-gas detection of ethane. Appl Phys B 2012;106:251–5.

[14] Fill M, Debernardi P, Felder F, Zogg H. Lead-chalcogenide mid-infrared vertical external cavity surface emitting lasers with improved threshold: theory and experiment. Appl Phys Lett 2013;103:201120.

[15] Rahim M, Khiar A, Felder F, Fill M, Zogg H, Sigrist MW. 5-μm vertical cavity surface-emitting laser (VECSEL) for spectroscopic applications. Appl Phys B 2010;100:261–4.

[16] Marinov D, Sigrist MW. Monitoring of road-traffic emission with mobile photoacoustic system. Photochem Photobiol Sci 2003;2:774–8.

[17] Gianella M, Sigrist MW. Chemical analysis of surgical smoke by infrared laser spectroscopy. Appl Phys B 2012;109:485–96.

[18] Gianella M, Hahnloser D, Rey JM, Sigrist MW. Quantitative chemical analysis of surgical smoke generated during laparoscopic surgery. Surg Innov 2014;21:170–9.

[19] Gianella M, Sigrist MW. Automated broad tuning of difference frequency sources for spectroscopic studies. Appl Opt 2011;50(4):A11–9.

[20] Gianella M, Sigrist MW. Improved algorithm for quantitative analyses of infrared spectra of multicomponent gas mixtures with unknown composition. Appl Spectrosc 2009;63:338–43.

[21] Kottmann J, Grob U, Rey JM, Sigrist MW. Mid-infrared fiber-coupled photoacoustic sensor for biomedical applications. Sensors 2013;13:535–49.

[22] Kottmann J, Rey J, Sigrist MW. New photoacoustic cell design for studying aqueous samples. Rev Sci Instrum 2011;82:084903.

[23] Kottmann J, Rey JM, Luginbühl J, Reichmann E, Sigrist MW. Glucose sensing in human epidermis using mid-infrared photoacoustic detection. Biomed Opt Express 2012;3(4):667–80.

[24] Rey JM, Kottmann J, Sigrist MW. Photothermal diffuse reflectance: a new tool for spectroscopic investigation of scattering samples. Appl Phys B 2013;112:547–51.