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Quantum Cascade Lab-on-a-Chip for Fluid Sensing Applications

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In our modern world miniaturization has taken place in various aspects of everyday life. Devices have not only become more powerful regarding computational performance but also gained the ability to detect physical properties of all sorts with the development of downscaled sensors. Extensive research in quantum cascade technology over the last two decades led to infrared lasers and detectors capable of enhancing that trend. In this work we present a monolithically integrated quantum cascade laser (QCL) and detector device for chemical sensing of fluids both inside a microfluidic cell (volume ~ 60 µl, comparable to one water droplet) as well as in-situ within a beaker.

The mid-infrared spectral region has proved extremely useful for highly-sensitive and non-destructive chemical sensing, since molecules show their strongest and distinct absorption features in this so-called "fingerprint region". QCLs can be designed to directly target these absorption lines, allowing measurements to discriminate between different molecule concentrations [1] and even distinguish structural differences e.g. the secondary structure of proteins [2].

With an appropriate design of a QCL active region the same material, when unbiased, can be used as a detector enabling efficient emission and detection of identical wavelength radiation [1]. A monolithically integrated QC laser and detector can additionally be merged with a dielectric loaded surface plasmon polariton waveguide to enhance the coupling efficiency of up to 45 % over 100 µm, while maximizing the analyte interaction volume [1]. Multiple individual units can be processed in parallel on a single wafer. Additionally, implementing distributed feedback gratings results in devices with individual wavelengths, yielding a small and cost-efficient sensor array.

Such a sensor array with an interaction path length of 50 µm has been implemented within a microfluidic cell (Fig. 1a) and for in-situ measurements (Fig. 1b), focusing on the downscaling of the devices. First proof of principle absorption spectroscopy measurements show promising results for water concentration (high absorption) in isopropyl alcohol (low absorption) determination for both concepts (Fig. 2). Two lasers ($\nu_1 = 1650\ cm^{-1}$, $\nu_2 = 1630\ cm^{-1}$) are operated simultaneously (5 kHz, 100 ns pulses) at room temperature, the respective detector signals are recorded over time. A third laser is used as a fast on-chip temperature sensor. Calibration curves were recorded and applied, leading to good agreement with the theoretical concentration transient. At high water concentrations the signals start to deviate and appear noisy due to the exponentially decaying nature of absorption. Additionally, the in-situ signal even allowed for single droplet detection and volume calculation.

[1] B. Schwarz et al., "Monolithically integrated mid-infrared lab-on-a-chip using plasmonics and quantum cascade structures", Nat. Commun. 5, 4085 (2014).

[2] A. Schwaighofer, et al. External cavity-quantum cascade laser infrared spectroscopy for secondary structure analysis of proteins at low concentrations. Sci. Rep. 6, 33556 (2016).

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