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Photoacoustic sensors efficiently detect trace gas

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Quantum-cascade lasers combined with photoacoustic spectroscopy allow for the design of compact, sensitive gas sensors for environmental applications.

Increasing awareness and new regulations for safety and emission control have created a strong demand for trace gas sensors that are compact and portable, as well as low cost and reliable. Quantum-cascade lasers (QCLs) have given new impetus to the development of optical gas sensors thanks to their tunability in the spectral region from 3-20μm (fingerprint region). QCLs show excellent properties in their narrow line width, average power (up to a few watts), and room-temperature operation. In combination with these laser sources, photoacoustic spectroscopy (PAS) offers the advantage of high sensitivity, selectivity, compact setup, fast time-response, and simple optical alignment.

PAS is based on the photoacoustic effect,[1] the conversion of light to sound in absorbing materials. Viengerov[2] used PAS for the first spectroscopic gas analysis in 1938. The photoacoustic signal is traditionally detected using a resonant acoustic cell equipped with a sensitive microphone.[3] Recently, alternative transducers such as a quartz tuning fork (TF),[4] optimized capacitive microelectromechanical systems microphones[5], or a silicon cantilever[6] have been demonstrated. We designed and fabricated photoacoustic gas sensors based on different setup configurations for detection of nitric oxide (NO) and formaldehyde (CH_2O). The devices exhibit state-of-the-art sensing performance.

The realized photoacoustic sensors use commercial QCLs as light sources. We have investigated different sensor schemes. One is based on resonant photoacoustic H- and T-cell sensors and electret microphones. Under resonant conditions, the cells work as an acoustic amplifier. The absorbed laser energy accumulates in the resonator's acoustic mode. The amplitude of the acoustic wave is scaled by a quality factor (Q) of 20–200.[7–12] An alternate scheme is based on quartz-enhanced photoacoustic spectroscopy (QEPAS). In this technique, the modulated laser light is focused between two prongs of a quartz TF, where the absorbing gas generates acoustic pressure waves that excite a resonant vibration and then are converted into an electrical signal by the piezoelectric effect.[13]

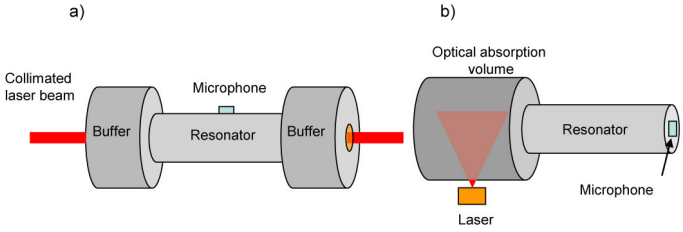

Figure 1. *Schematic of the photoacoustic a) H-cell and b) T-cell sensors.*

The resonant photoacoustic cell characterized by H-cell geometry consists of a cylindrical stainless steel resonator with two $\lambda/4$ long buffer volumes connected to its ends. This configuration helps to reduce the background signal, via destructive interference, caused by the heating of the two zinc selenide (ZnSe) windows.

We designed the resonator to be excited in its first longitudinal mode (1380Hz). It was equipped with four electret microphones placed on the antinode of the acoustic mode (see Figure 1a). We used the sensors to detect NO and CH_2O down to 150 parts per billion (ppb).

The resonant T-cell consists of two intersecting volumes: an optical-absorption volume and an acoustical-resonance cylinder. The internal gold-coated walls of the optical cavity have been shaped to produce multiple light reflection and subsequent focusing in the cavity center. An electret microphone is mounted at the end of the resonance cylinder in a design that does not require a collimated laser beam (see Figure 1b). Using this configuration, we saw a five times better detection limit (30ppb) for CH_2O.

Another group developed a QEPAS NO sensor using a continuous-wave, thermoelectrically cooled, external-cavity QCL light source[13] (see Figure 2). To enhance the QEPAS signal,

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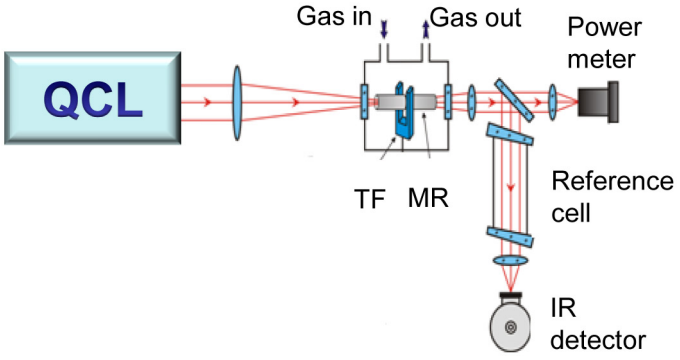

Figure 2. *Schematic of the quartz-enhanced photoacoustic spectroscopy sensor and the quantum-cascade laser (QCL). TF: Tuning fork. MR: Microresonator.*

We coupled the TF with an acoustic-organ-pipe type of microresonator (MR). The QEPAS spectrophone, consisting of the TF and the MR, was put inside a vacuum-tight cell with ZnSe windows. A NO concentration of 15 ppb resulted in a noise-equivalent signal.

In summary, the development of compact gas sensors is important for environmental applications. We developed two different approaches using QCLs for sensing trace NO and CH_2O. The former was based on standard PAS and resonant cells. The result was a better detection limit using an innovative T-cell. The second approach was based on QEPAS, with the sensor's detection sensitivity at 15ppb. Future improvements will involve implementing a low-loss, mid-infrared, single-mode fiber system to couple the QCL source with the spectrophone and convert our sensor into a portable device.

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