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Using Photoacoustic Wave Interference to Improve the Signal-to-Noise Ratio in Gas Sensors

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Summary:
Photoacoustic-based gas sensors are particularly suited to detect molecules with strong absorption features in the mid infrared spectral range. Especially indirect photoacoustic setups allow for building miniaturized, low-cost detectors. When using mid-IR LEDs as a light source, their low optical output power results in poor Signal to Noise Ratio (SNR), which is currently a limiting factor in terms of performance. In this contribution we make use of the properties of state-of-the-art MEMS microphones and the potential for modulating arbitrary waveforms in LEDs to demonstrate how the SNR may be improved.

Keywords: noise, interference effects, sensors using photometry, processing of wave sensor data

Introduction

Even though photoacoustic-based gas sensors have been used in a variety of applications for more than 80 years, the potential of the technique in terms of miniaturization and selectivity has not been explored to its full extent. In recent years, academic and commercial efforts in direct and indirect photoacoustic spectroscopy have led to ever smaller and better performing devices.

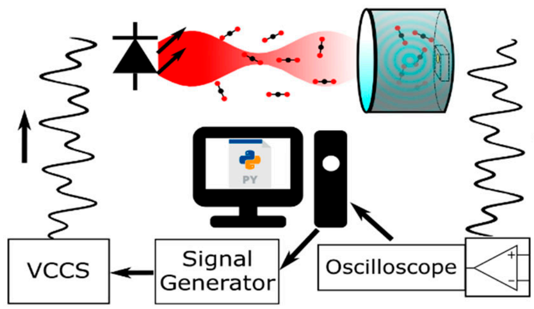

Fig. 1. Schematic diagram of the system used. Arbitrarily generated waveforms are sent as current waveforms to an LED using a Voltage-Controlled Current Source (VCCS). The photoacoustic signal resulting is amplified, then detected by an oscilloscope.

In photoacoustic non-dispersive infrared absorption spectroscopy (NDIR) setups the selectivity is mainly governed by the gas filling, which in turn opens up the possibility to use simpler light sources, e.g. thermal emitters or Light Emitting Diodes (LEDs). However, cross-sensitivities may arise when using thermal emitters as a consequence of overlapping spectral features between gases [1]. Therefore, the use of LEDs as a light source is beneficial, since their spectral range is much more limited. Additionally, current thermal emitters do not allow for modulation frequencies exceeding some tens of Hertz [2].

Currently, the optical output power of LEDs in the mid infrared spectral range is still limited to below 1 mW. Additionally, too high a modulation frequency is not desirable, because the photoacoustic signal strength decays as $1/\omega_{mod}$. Due to these factors, only reducing the noise on the sound transducer signal remains to improve the signal-to-noise ratio (SNR) for a given optical path.

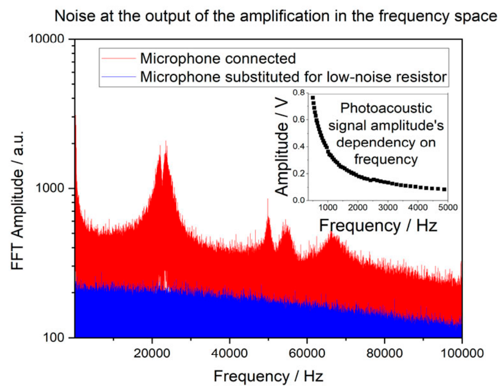

Fig. 2. Noise characterization of the detector and amplification. The dominating noise source is intrinsic to the MEMS microphone, especially at the low (<1kHz) frequencies that are used for photoacoustics because of the 1/f decaying signal amplitude. The resonant peaks of this microphone while surrounded by a CO_2 atmosphere can be observed.

In the past, quartz tuning forks have been used in indirect photoacoustic setups but their resonance frequencies are usually in the kHz range, which offsets the advantage of their resonance due to the decaying photoacoustic amplitude. Alternatively, commercially available MEMS microphones feature a near constant sensitivity in the audible acoustic spectrum. In the past, this microphone type has been utilized to gauge the photoacoustic wave but so far, no use has been made of the capabilities of those sensors in terms of detecting various acoustic frequencies simultaneously.

System Design

The basic setup used is depicted in Figure 1 and consists of a simple, indirect photoacoustic setup with the aim to study methods to reduce the noise of the photoacoustic signal.

This system uses a mid-infrared LED from Hamamatsu Photonics with a central emission wavelength of 4.2 µm and a spectral width of ~1 µm. The photoacoustic detector is a hermetically sealed cell filled with 100% CO_2, a sapphire window for optical access, and an ICS-40720 MEMS microphone from InvenSense as sound transducer. The photoacoustic signal's amplitude is small enough to require the use of a low-noise, multi-stage, wideband amplification.

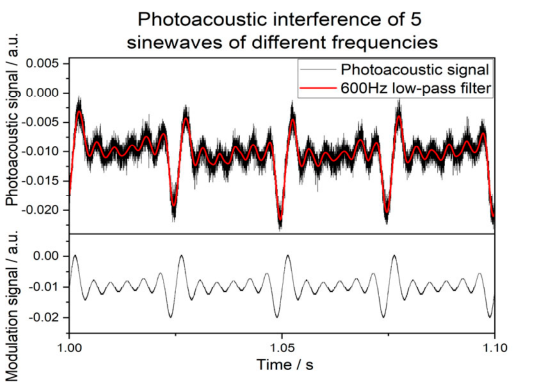

Fig. 3. Interference of 5 different sinewaves in the photoacoustic cell (above), and original modulation signal (below). Even for high numbers of interfering signals the rough shape of the current signal is preserved, with a growing degree of distortion at higher numbers of different frequencies.

Results

The amplifier circuit has been characterized to prove that most of the noise comes from the microphone, which is the limiting factor in the electronic circuit in terms of SNR. The results of this noise characterization can be observed on Figure 2, as well as the dependency of the photoacoustic signal with the modulation frequency.

Afterwards, it has been established that interference of different frequencies can take place inside the photoacoustic cell, by adding several sinewaves together at the generation of the waveform in the arbitrary signal generator. The results can be found on Figure 3.

Finally, whether or not interfering signals can increase the SNR has been studied using square-wave waveforms, which upon interference don't generate high peaks of current that could damage the light source. First a modulation frequency of 80Hz has been chosen, as it roughly maximizes the SNR for this particular microphone and configuration. A sine wave and a square wave of 100mA peak to peak and 80Hz frequency have been compared. Fourier analysis has been carried out for both waveforms as shown in Figure 4, and it has been established that a minimum 14% increase in SNR without increasing power consumption is possible for the used system.

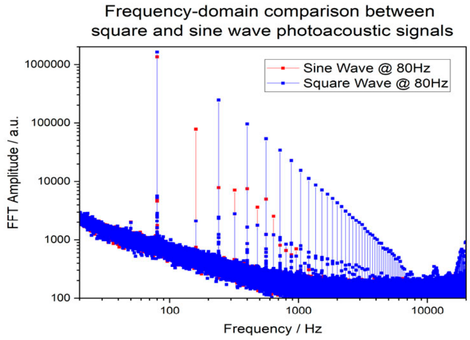

Fig. 4. Photoacoustic frequency spectrum for a sine and a square wave. The harmonics of the sinewave are due to distortion in the photoacoustic cell at low frequencies. The difference in amplitude between the harmonics of both waveforms is noticeable.

Conclusions

The combined use of LED as light source and MEMS microphones as sound transducer offers unique possibilities to improve the performance of low-cost, miniaturized NDIR-type photoacoustic gas sensors. Taking into account higher harmonics resulting from square wave form modulation, the SNR may be improved. The use of interference effects in photoacoustic detector has been explored here and has the potential for further improvements.

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