Resonant Photoacoustic Detection of NO₂ with an LED Based Sensor [†]

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Abstract: In times of steadily increasing air pollution especially in urban areas, the monitoring of nitrogen dioxide (NO₂) has gained in importance and with it the search for compact, low-cost sensors. We present a novel approach to measure NO₂ in sub-ppm concentrations with a photoacoustic sensor utilizing a T-shaped resonance cell. An inexpensive single LED with a peak wavelength of 410 nm was used as radiation source and the acoustic detection was done with a commercial MEMS microphone. For optimal coupling of the divergent LED light into the cell, the T-shaped resonator was developed and fabricated with rapid prototyping methods. The resonator shows a acoustic Q-factor >10 while having nearly no zero gas signal.

Keywords: resonant photoacoustic sensor; LED; NO₂ detection

1. Introduction

NO₂ is a highly toxic gas, which originates mostly from combustion processes in power plants or motor vehicles. Because NO₂ can already be hazardous in concentrations of only a few parts per million (ppm), it is necessary to monitor the NO₂ concentration in the environment whenever these processes take place in confined spaces, e.g., underground parking garages or road tunnels [1]. Today, NO₂ is measured by electrochemical sensors or large absorption photometers. Electrochemical sensors show a high sensitivity to NO₂ and they are small and cost effective, but require a frequent replacement, due to their limited lifetime. IR-absorption photometers on the other hand need an absorption path of several meters to gain a sufficient sensitivity, which makes them costly and very large.

The resonant photoacoustic sensor we present reaches a high sensitivity with the usage of a low cost LED and a commercial MEMS microphone. Due to the optical measurement principle, it is very stable and shows low drift effects. For an efficient coupling of the light into the cell, we present a T-shaped resonator design with a resonance frequency in the kHz range.

2. Design and Methods

2.1. Sensor Design

Photoacoustic measurements profit from a high signal to offset ratio. The radiation that is irradiated into the cell is absorbed not only by the gas, but also by the cell itself (e.g., the cell walls or the windows). This absorption results in an interfering signal offset [2].

To solve this issue for divergent sources like LEDs, we use a T-shaped cell, which consists of an absorption chamber and a perpendicular cylindrical resonator. Figure 1a shows the cross section of the proposed T-shaped cell structure. In this design, the resonator has a pressure node at the point where it enters the absorption chamber and a pressure trough at the end where the microphone is mounted. The dimensions of the cell were determined by raytracing simulations using ZEMAX and acoustic FEM simulations with ANSYS. For our sensor setup, an absorption chamber diameter of 20 mm and a length of 30 mm were chosen. With a length of 68 mm, the resonator was designed to have its third mode at approximately 6 kHz. The cell was fabricated out of aluminum with an SLM rapid-prototyping process. The used microphone is a bottom port microphone (ICS-40720, TDK, Tokyo, Japan). It is soldered onto a PCB that is mounted at the closed end of the resonator. The light source is a 15335340AA350 type LED by Würth Electronic. It has a peak wavelength of 405 nm and is driven by a sinusoidal current with 200 mA peak. The resulting low peak power allows a passive cooling of the LED. A combination of three lenses focus the light into the cell: one with 15 mm and two with 25.4 mm focal length. Figure 1b shows the sensor setup that was used in the measurements.

Figure 1. (a) CGI-rendered cross-section of a resonant photoacoustic T-shaped cell design. The absorption chamber has a large diameter, optimized for the ray diameter of divergent sources like LEDs. (b) Sensor setup with resonant cell, LED, lenses and the microphone on a PCB.

The microphone signal is preamplified, AD-converted and digitally processed on a custom board, that also generates the signal to modulate the LED current. The captured microphone signal is filtered by a digital lock-in algorithm, and transmitted to a PC.

2.2. NO₂ Gas Measurements

In order to determine the frequency response of the resonant cell and the resolution of the sensor, gas measurements were performed at Fraunhofer IPM. The frequency response is measured by applying a permanent flow of 22.5 ppm NO₂ at 0.1 L/min through the cell while sweeping the LED modulation frequency from 3 kHz to 10 kHz.

For the resolution measurement, the cell is perfused with alternating steps of 100% nitrogen and different NO₂ concentrations in N₂ ranging from 850 ppb to 4300 ppb. The sweep in this measurement covers just the frequency range of one resonance peak, while one single point in the sweep is sampled for around 1.5 s. In a simple algorithm, the maximum point of a sweep is considered to be the maximum of the sweep. This approach eliminates the need for active resonance tracking on the cost of a much lower data rate. All captured data points are lock in raw data without any compensation or calibration applied.

3. Results and Discussion

Figure 2 shows the results of the frequency response measurement. The third mode is with 6.2 kHz close to the design target of 6 kHz. The other modes are also close to the predicted frequencies, but the third mode amplifies the signal less than expected. The second mode gives the best signal amplification, having a Q-factor of 12.4.

Figure 2. Frequency response of the resonant photoacoustic cell. The second resonator mode gives the best signal and has a Q-factor of around 12.4.

Due to the high amplification, the second mode was chosen as frequency range for the gas measurement. Figure 3 shows the result which was obtained. The standard deviation of the signal is in the complete measurement below 5 counts, while the sensitivity can be determined to 120 counts/1000 ppb. This leads to a noise equivalent concentration of 32 ppb, resulting in a resolution of around 200 ppb (6σ). Due to stray light, there is a zero gas offset of 370 counts. Despite this offset, there is no observable drift in the zero signal during the measurement time of five hours.

Figure 3. Gas measurement result of the photoacoustic sensor. Due to the sweeping over the complete resonance peak the data rate is around 0.25 min^{-1} . The noise analysis showed a noise equivalent (1σ) of approximately 32 ppb. Therefore the sensor can detect concentrations around 200 ppb with 6σ confidence.

The data rate of the measurement was rather low with the simple algorithm with one data point every four minutes. The algorithm used one of 200 points per sweep to represent the gas

concentration. With an intelligent tracking algorithm, the data rate could be increased to 1–10 s without any loss of resolution.

4. Conclusions

Our investigations show that it is possible to use a photoacoustic detection principle with low cost components to detect nitrogen dioxide in concentrations well below one ppm. We developed a photoacoustic sensor, using an LED at 405 nm wavelength and a MEMS microphone. To gain a high resolution, a resonant cell design suitable for divergent sources was designed. Test measurements with the sensor showed a resolution (6σ) of 200 ppb while no drift of the zero gas signal was observed. With regard to the low cost components, our photoacoustic sensor could be an alternative to electrochemical sensors in NO₂ monitoring applications.

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Conflicts of Interest: The authors declare no conflict of interest.

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