

Dual-Resonance Indirect Photoacoustic Gas Sensing System for Sub-ppm Gas Detection

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Summary:

This work presents a dual-resonance photoacoustic (PA) gas sensing system that exploits the spectral overlap between resonances of a photoacoustic cell and a piezoelectric MEMS cantilever to achieve enhanced sensitivity for carbon dioxide detection. The system employs a chopper-based modulation and a distributed feedback (DFB) laser operating near 4225 nm, targeting a strong absorption line of carbon dioxide. Lock-in-based photoacoustic measurements demonstrate a detection resolution of ca. 250 ppb of carbon dioxide in nitrogen at atmospheric pressure.

Keywords: Photoacoustic gas sensing, Dual resonance, Piezoelectric MEMS cantilever, Acoustic resonator, Carbon dioxide detection

Introduction

Photoacoustic spectroscopy (PAS) is a trace gas detection technique in which modulated infrared radiation absorbed by target gas molecules generates a periodic acoustic pressure wave whose amplitude is proportional to the gas concentration [1]. Conventional systems exploit a single resonance—either an acoustic cell mode or a detector mechanical mode—to amplify the signal. However, the achievable quality factor at a single resonance is limited by viscous and thermal losses in miniaturized geometries [2]. In this work, a dual-resonance approach is presented in which the first fundamental resonance mode of a custom acoustic cell is deliberately matched to the fundamental resonance of a piezoelectric MEMS cantilever. At the shared frequency, both amplification mechanisms act simultaneously, yielding a multiplicative signal enhancement. Sub-ppm CO₂ detection is demonstrated using a DFB laser near 4225 nm with a chopper and amplitude modulation scheme, achieving a resolution of 250 ppb.

System Design and Operating Principle

The sensing system, shown in Fig. 1, comprises a modified photoacoustic resonator cell and a piezoelectric MEMS cantilever transducer. The resonator cell is an H-shaped structure with a central front cavity illuminated by the laser beam, connected via a narrow neck to a larger back volume. An adjacent narrow channel also connects the front volume to the reference microphone. The cell geometry is dimensioned such that its damped first fundamental mode coincides with the first flexural resonance of the cantilever. The dampness comes due to the introduction of a

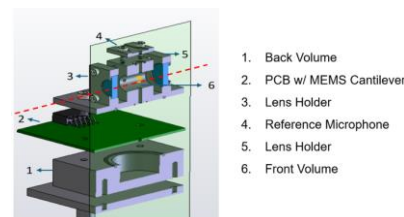


Fig. 1. CAD cross-section of the PA system

MEMS cantilever in between the cell neck and the back volume. The dual-resonance operating point thus yields an overall enhancement proportional to $Q_{\text{CellDamp}} \times Q_{\text{cant}}$ relative to the off-resonance baseline.

Laser Source and Target Line

The target absorption line was selected using the HITRAN spectroscopic database [3]. Fig. 2 shows the laser power as the function of current and also the targeted CO₂ absorption spectrum in the mid-infrared region [4]. A specific line near 4.22 μm ($\sim 2370 \text{ cm}^{-1}$) was chosen for its strong line strength and minimal interference from other gas species.

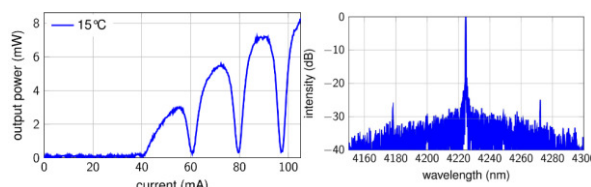


Fig. 2. DFB laser & gas absorption parameters

Experimental Setup

The DFB laser beam is modulated by a mechanical chopper at the dual-resonance frequency. In the indirect configuration presented here, the modulated beam passes through the measurement channel with variable and controlled CO₂

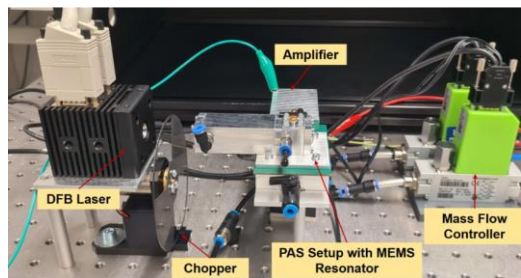


Fig. 3. PAS system measurement setup

gas concentration, prepared using known gas mixtures and mass flow controllers, and a resonant cell (which doubles as a reference chamber) containing high concentration (>80%) CO₂. The photoacoustic pressure wave generated within the cell drives the MEMS cantilever, whose piezoelectric output voltage is demodulated by a lock-in amplifier referenced to the chopper frequency. The in-phase and quadrature signal components are recorded as a function of gas concentration. The temperature and humidity of the setup are monitored using a reference sensor. The separation of variable gas volume with the reference gas volume ensures minimal influence on the position of the resonance frequency. This is further also corroborated by the use of the phase-locked loop technique.

Results and Discussions

The dual-resonance design was first validated through independent frequency sweep characterization. The cell transfer function was measured using PAS signal and a reference microphone.

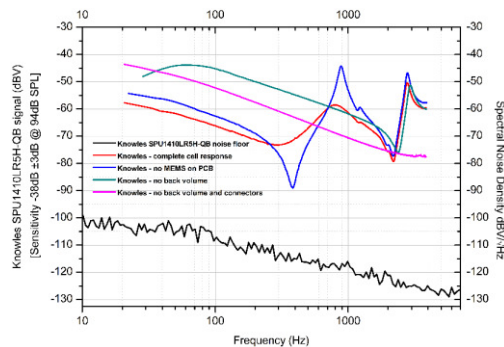


Fig. 4. Influence of different components on the mea-

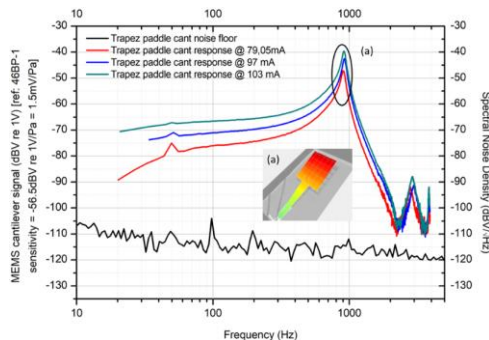


Fig. 5. Overlapped PAS frequency response of the trapezoidal cantilever w/ the cell resonance at different laser currents

Fig. 4 presents both cell responses in different configurations and the combined system transfer function, confirming spectral overlap at the target frequency ($f_{\text{res}} \sim 910$ Hz). The combined quality factor at the matched point is significantly higher than that of either subsystem alone. For example, the complete cell response shown by the red curve in Fig. 4 can be compared to the cantilever response in Fig. 5. The signal-to-noise ratio (1 Hz BW) for the current generation of cantilevers at f_{res} is ~ 72.5 dB for > 80% CO₂ in the reference chamber. This is forecasted to improve with the next generation of cantilevers with better material parameters.

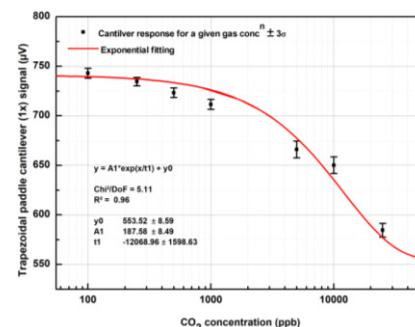


Fig. 6. PAS signal vs. CO₂ concentration @ f_{res}

The photoacoustic sensing performance was evaluated by varying the CO₂ concentration from ambient levels to sub-ppm. Fig. 5 presents the lock-in amplifier output versus concentration. An expected negative exponential relationship, following Beer-Lambert's law, is observed between the cantilever signal and change in the gas concentration. With a $\pm 3\sigma$ deviation, the 250 ppb of CO₂ is distinctly and repeatably measurable.

Conclusions

A dual-resonance photoacoustic gas sensor has been demonstrated by spectrally matching a first fundamental cell acoustic mode with a MEMS cantilever mechanical resonance, yielding multiplicative signal enhancement. Using a mid-infrared DFB laser near 4225 nm targeting a HITRAN-identified CO₂ absorption line and a chopper-based AM scheme, a detection resolution of 250 ppb was achieved. This work offers a strategy towards highly selective, high-sensitivity photoacoustic sensors, which can be extended to different target gases.

References

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