Low frequency MEMS used as detector in photoacoustic spectroscopy

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Abstract: This study presents low-frequency MEMS devices for photoacoustic spectroscopy, reducing relaxation distortions and enhancing gas detection sensitivity. Using N_2O as a test case, the system achieved 3 ppb sensitivity, demonstrating potential for environmental monitoring applications.

Photoacoustic spectroscopy (PAS) has emerged as a leading method for trace gas detection due to its compact design, high sensitivity, and inherent absence of background noise, making it highly suitable for applications in environmental monitoring, medical diagnostics, and security. However, the performance of PAS is significantly affected by molecular relaxation dynamics, particularly for slow-relaxing species or when acoustic transducers operate at high frequencies. These relaxation effects can distort the photoacoustic signal, reduce sensitivity, and complicate quantitative analysis. While advanced multivariate techniques have been proposed to address these issues [1], reducing the acoustic resonance frequency remains one of the most effective strategies to minimize distortions caused by relaxation dynamics [2].

This study introduces the development and characterization of two innovative low-frequency spring-like MEMS devices designed to function as microphones in a PAS setup. The MEMS devices, which differ only in scale, exhibit fundamental mechanical resonances at 0.5 kHz and 3 kHz, respectively. This significantly mitigates the impact of incomplete vibrational-to-translational relaxation, enabling more precise and stable gas concentration measurements. A continuous wave quantum cascade laser, tuned to a strong N_2O rovibrational transition at 2189.273 cm^{-1}, was employed as the excitation source, while MEMS displacement was monitored using a balanced Michelson interferometer. Two detection strategies were explored: 1f amplitude modulation (1f AM) using an acousto-optic modulator and 2f wavelength modulation (2f WM) via direct laser current modulation. Experimental results revealed that both methods achieved similar performance, with noise equivalent absorption coefficients (NNEA) of approximately 10^{-7} $cm^{-1}\cdot W\cdot Hz^{-1/2}$ in optimal conditions. Moreover, 2f WM demonstrated practical advantages by eliminating the need for an optical isolator and AOM, preserving optical power, and simplifying the optical setup. Under optimal conditions, the system achieved a detection sensitivity of approximately 3 ppb with an integration time of 100 seconds. The detection limit achieved is less than 100 times the natural abundance of N_2O in the atmosphere, confirming the feasibility of this MEMS-based approach for real-world environmental monitoring.

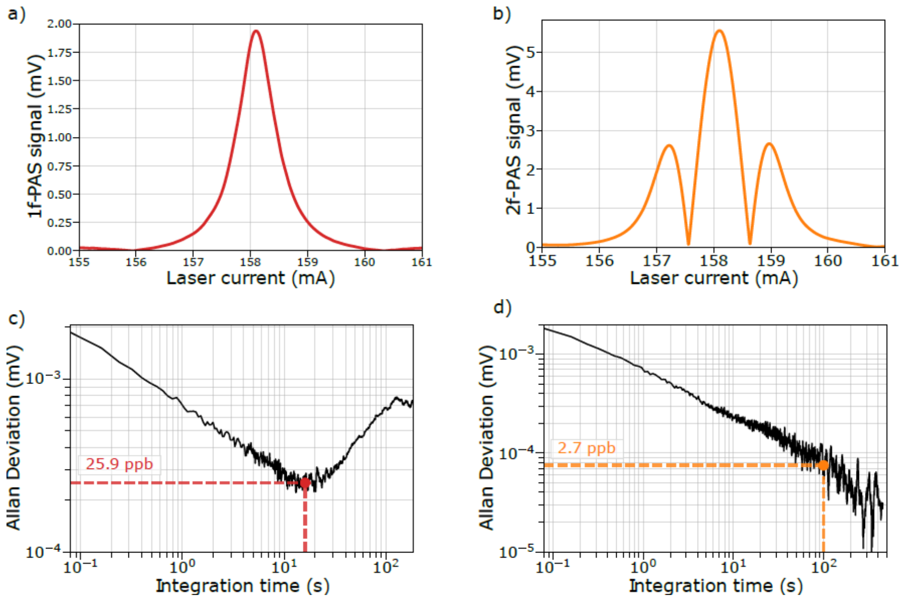

Figure 1. PAS signal obtained in amplitude modulation (a) and frequency modulation (b) with the 3-kHz MEMS in the optimal conditions. Allan-Werle deviation analysis obtained for the 1f AM (c) approach and 2f WM (b) approach, respectively.

References

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[2] Dello Russo, Stefano, et al. "Quartz-enhanced photoacoustic spectroscopy exploiting low-frequency tuning forks as a tool to measure the vibrational relaxation rate in gas species." *Photoacoustics* 21 (2021): 100227.