Simulation and determination of the coupling efficiency to photoacoustic resonators

Daniel Sieg[1], Vincent Kuczius[1], Gabriel Rodriguez Gutierrez[1], Jonas Gaworski[1], Stefan Palzer[1]
[1] TU Dortmund, Professorship for Sensors, Friedrich-Wöhler-Weg 4, 44227 Dortmund, Germany
stefan.palzer@tu-dortmund.de

Summary:

Direct photoacoustic spectroscopy setups oftentimes employ acoustic resonators to enhance the photoacoustic signal and suppress acoustic noise from the environment. In this contribution the coupling of an idealized sound source to a cylindrical resonator is simulated and shows the dependence of the coupling efficiency on the relative position of the sound source with respect to the resonator. The simulations reveal the spatial dependence of the ideal incoupling positions as a function of the resonator modes. The results are important for setups that spatially separate acoustic sound generation and detection.

Keywords: direct photoacoustic spectroscopy, acoustic resonator, coupling simulation

Introduction

The use of resonator-enhanced, direct photoacoustic spectroscopy setups for gas monitoring is a versatile tool for sensitive [1] detection of the molecular number density. Laser or light emitting diode (LED) – based devices have been shown to achieve limits of the detection in the ppb range [2,3]. For scenarios, where the spectral bandwidth of the exciting light source is much narrower than typical absorption features, the performance in terms of selectivity exceeds that of indirect photoacoustic setups [4] and consequently, it is a complementary technology in this regard.

Typically, the photoacoustic wave generation is done within the acoustic resonator, i.e. the exciting light is funneled into the acoustic resonator, where it is absorbed according the Beer-Lambert law [5] ultimately leading to the generation of an acoustic wave, whose amplitude indicates the number density of the target molecules. A large overlap between the acoustic eigenmodes of the resonator and the light beam achieves an excellent coupling efficiency in case the overall absorption is weak, leading a nearly constant sound wave amplitude along the absorption path.

However, in case of strong absorption, the light absorption leads to exciting the molecules localized. In this case, the signal detected with a microphone may even decrease with increasing number density, since the coupling between generated sound wave and the resonator eigenmodes is weak.

In these cases, spatial separation of the sound wave generation and the acoustic resonator may offer systematic advantages, since signal generation and signal detection may be optimized independently. This may also be of relevance in setups aimed at detecting multiple gases with a single resonator [6]. In this case, the efficiency of coupling acoustic waves into a resonator becomes crucial. To this end, a simulation of a point-like sound source has been used to investigate the efficiency of photoacoustic wave coupling into acoustic resonators.

Setup of the Model

The simulation model is depicted in Figure 1 and features a point-source of sound in the vicinity of a cylindrical resonator.
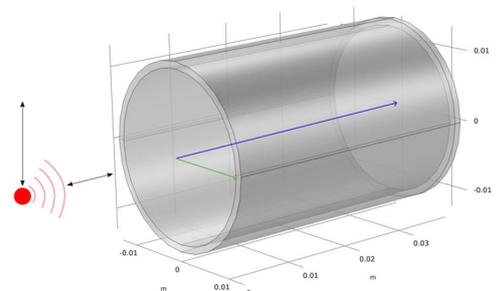

Fig. 1. The photoacoustic signal is modelled as a point source and the coupling efficiency into the resonator's eigenmodes is investigated as function of the distance from the opening and the radial offset from the symmetry axis.

The mode spectrum of a resonator with a diameter of 20 mm and a length of 35 mm is simulated in a modulation frequency range ω_{mod} between 2 kHz – 25 kHz. The amplitude of the different excited eigenmodes is used as a means to quantify the coupling efficiency as a function of the position of the sound source. Fig. 2 shows the frequency spectrum of the resonator.
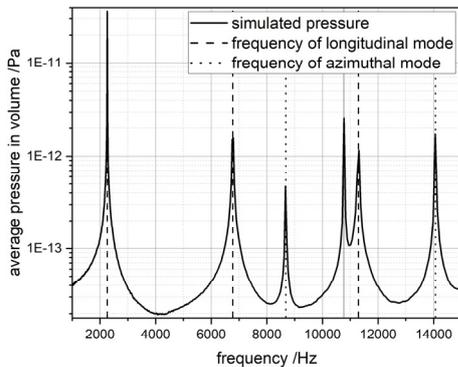

Fig. 2. The frequency spectrum of the longitudinal and azimuthal modes of the acoustic resonator.

The simulation results have been checked by exciting sound waves using a capacitor and a MEMS microphone inside the resonator. By scanning the excitation frequency of the capacitor, sound waves of equal frequency have been generated and the response to a frequency sweep has been analyzed using a Lock-In Amplifier.

Results

The spatial dependence of the efficiency of exciting acoustic waves inside the resonator as a function of the relative position of the sound source is depicted in Figure 3 and 4 for the longitudinal eigenmode at 13867 Hz and the azimuthal eigenmode at 20830 Hz in longitudinal and radial direction, respectively.
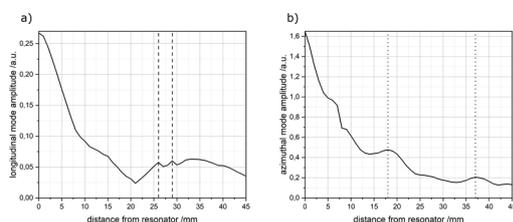

Fig. 3. Coupling efficiency to the longitudinal (a) and azimuthal (b) mode as a function of the longitudinal displacement.
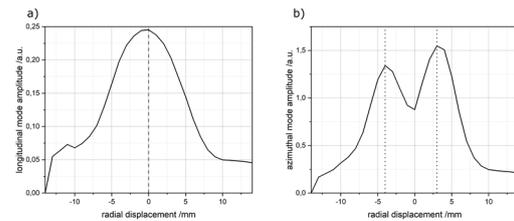

Fig. 4. Coupling efficiency to the longitudinal (a) and azimuthal (b) mode as a function of the radial displacement.

The measurements show fundamentally different behavior of the spatial dependence of the coupling efficiency for different classes of eigenmodes.

Conclusion

The spatial decoupling of photoacoustic signal generation and detection offers means to independently optimize the dynamic range and sensitivity of direct photoacoustic setups. The coupling efficiency hinges on the relative position of the sound source and may be tuned in order to optimized schemes for multigas detection further.

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