

Nodal-Line Slit-Patterned Open Photoacoustic Cell for Mode Selectivity

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Abstract

Open photoacoustic cells enable rapid gas exchange and continuous-flow operation but often suffer from reduced acoustic selectivity and increased susceptibility to external acoustic disturbances. In this work, we present a modified open photoacoustic resonator in which longitudinal slits are introduced along the mantle of a cylindrical cavity. Rather than serving solely as gas inlets, the slits are positioned along the nodal lines of a selected acoustic eigenmode, enabling passive, geometry-driven mode selectivity.

The acoustic behavior of the proposed design was investigated using a Pressure Acoustics interface in COMSOL Multiphysics®. An eigenfrequency analysis was first performed to identify the relevant resonant modes and determine the nodal-line locations of the selected target mode. Frequency-domain simulations were then used to evaluate the acoustic pressure response of resonators with and without slit patterning. The numerical model of the reference resonator was experimentally validated using photoacoustic measurements with water vapor as the absorbing gas.

The simulations show that the slit arrangement affects the investigated acoustic modes in different ways. The target resonance is largely preserved because the openings coincide with regions of low acoustic pressure, whereas competing modes with significant pressure amplitudes at the slit positions couple more strongly to the surrounding acoustic domain and experience increased radiation losses. Consequently, the resonant response of the competing mode is suppressed relative to that of the target mode. A parametric investigation of the slit width further indicates that the relative amplitudes of the modes can be controlled geometrically and suggests an optimal slit width that maximizes the target-to-competing-mode amplitude ratio.

The presented approach provides a simple passive method for tailoring the modal characteristics of open photoacoustic resonators while retaining the advantages of open-cell operation. The results demonstrate the potential of nodal-line slit patterning for improving modal selectivity and provide a basis for further optimization and experimental validation of the slit-patterned resonator.

Keywords: Photoacoustic spectroscopy, open photoacoustic cell, acoustic mode selectivity, acoustic resonance, finite element method, COMSOL Multiphysics®

Introduction

Photoacoustic spectroscopy (PAS) is a highly sensitive method for detecting trace gases, converting modulated optical absorption into an acoustic pressure signal. The performance of a resonant photoacoustic system is strongly influenced by the geometry of the acoustic cell, which determines resonance enhancement, gas-exchange characteristics, acoustic losses, and the coupling of acoustic modes to the surrounding environment.

Conventional resonant photoacoustic cells are typically closed or only weakly open to maintain a high acoustic quality factor and reduce the influence of external acoustic disturbances. However, such configurations can restrict gas exchange, thereby limiting response time in applications involving continuous flow or rapidly varying gas concentrations. Open photoacoustic cells provide an alternative by enabling efficient gas exchange and have been demonstrated for measurements in both

flowing and non-flowing environments [1, 2, 3]. However, their increased acoustic coupling introduces additional loss channels and makes control of the acoustic modal structure an important aspect of open-cell design [4, 5, 6, 7].

The present work builds on the fully opened photoacoustic resonator introduced by Bozóki et al., which enables fast gas concentration measurements while maintaining a usable resonant photoacoustic response [2]. Here, the cylindrical resonator is modified by introducing longitudinal slits along its mantle. In contrast to openings introduced solely for gas exchange, the slit positions are selected based on the nodal-line structure of the targeted acoustic eigenmode. At these locations, the pressure variation associated with the targeted mode is small, and the openings are therefore expected to perturb this mode only weakly. Competing modes with significant acoustic pressure at the slit positions, in contrast, can couple more strongly to the surrounding acoustic domain and consequently experience increased acoustic losses.

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In this study, the nodal-line slit-patterning concept is investigated numerically using eigenfrequency and frequency-domain analyses in COMSOL Multiphysics®. The numerical model is experimentally validated using photoacoustic measurements of the reference resonator, with water vapor as the absorbing gas. The influence of slit width on the acoustic response is then investigated parametrically. The objective is to demonstrate that appropriately positioned longitudinal openings can provide passive, geometry-driven mode selectivity while retaining the fast gas-exchange characteristics and practical accessibility of an open photoacoustic resonator.

Brief theory of photoacoustics

In photoacoustic spectroscopy, intensity-modulated optical radiation is absorbed by the sample, exciting molecular energy levels. When collisional relaxation dominates the deactivation process, the absorbed energy is transferred to the translational motion of the surrounding gas molecules, resulting in periodic local heating and thermal expansion. The resulting pressure fluctuations generate an acoustic wave that can be resonantly enhanced when the modulation frequency approaches an acoustic eigenfrequency of the photoacoustic cell.

Under the assumptions of linear acoustics, the generation and propagation of the photoacoustic pressure field can be described by the inhomogeneous wave equation

$$\nabla^2 p(\mathbf{r}, t) - \frac{1}{c^2} \frac{\partial^2 p(\mathbf{r}, t)}{\partial t^2} = -\frac{\gamma - 1}{c^2} \frac{\partial H(\mathbf{r}, t)}{\partial t}, \quad (1)$$

where p is the acoustic pressure, c is the speed of sound, γ is the ratio of specific heats, and H represents heat density deposited by optical absorption [8, 9]. For harmonic excitation at angular frequency (ω), Fourier transformation yields the inhomogeneous Helmholtz equation

$$\left(\nabla^2 + \frac{\omega^2}{c^2} \right) p(\mathbf{r}, \omega) = \left(\frac{\gamma - 1}{c^2} \right) i\omega H(\mathbf{r}, \omega), \quad (2)$$

The resonant response of the cell is governed by its acoustic eigenmodes, whose spatial pressure distributions are determined by the resonator geometry and acoustic boundary conditions. Each mode contains regions of high acoustic pressure amplitude as well as nodal lines where the acoustic pressure approaches zero. In the proposed design, longitudinal slits are positioned along the nodal lines of the targeted mode. Since the acoustic pressure amplitude of this mode is small at the openings, the slit pattern is expected to perturb the targeted resonance only weakly. Modes exhibiting significant pressure amplitudes at the same locations can couple more strongly to the surrounding acoustic domain

and consequently experience greater acoustic losses. The slit arrangement can therefore provide passive, geometry-driven mode selectivity.

Numerical Model

The numerical model was developed in COMSOL Multiphysics® 6.3 using the Acoustics Module. A three-dimensional model was constructed to investigate the acoustic behavior of the open photoacoustic resonator. The acoustic field was modeled using a Pressure Acoustics interface under the assumptions of linear acoustics. A thermally conducting and viscous fluid model was used to account for bulk thermal and viscous losses in the acoustic domains. The numerical workflow consisted of an eigenfrequency analysis to identify the relevant acoustic modes and their spatial pressure distributions, followed by frequency-domain simulations to compute the cell's photoacoustic response. The validated frequency-domain model was subsequently used to investigate the influence of the proposed slit-patterned geometry on the acoustic response.

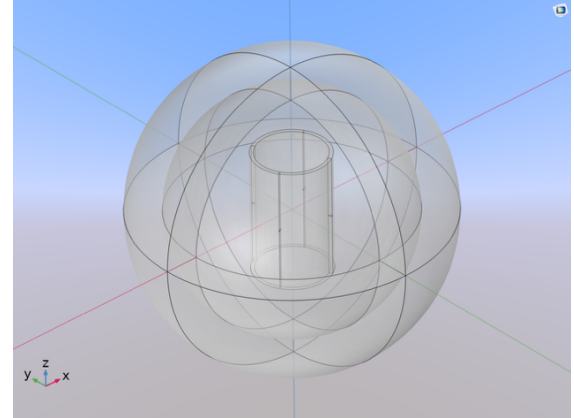


Figure 1. Computational domain of the geometry.

Geometry and Materials

The reference photoacoustic resonator was modeled as a cylindrical tube with a length of 50 mm, an inner radius of 14 mm, and a wall thickness of 1.5 mm. The resonator was embedded in a spherical computational domain with a radius of $4r_{\text{outer}}$, corresponding to 62 mm, to account for acoustic wave propagation and radiation into the surrounding environment. The outer layer of the spherical domain was implemented as a perfectly matched layer (PML) to absorb outgoing acoustic waves and minimize artificial reflections from the outer boundary. The PML thickness was defined as half of the maximum wavelength,

$$t_{\text{PML}} = \frac{\lambda_{\text{max}}}{2}, \lambda_{\text{max}} = \frac{c_0}{12 \text{ kHz}}, \quad (3)$$

$c_0 = 343 \text{ m/s}$ is the speed of sound. This resulted in a PML thickness of approximately 14.3 mm. The internal volume of the resonator and the surrounding

acoustic domain were modeled as air at a temperature of 293.15 K and an ambient pressure of 1 atm. The geometry is shown in Fig. 1.

Eigenfrequency Analysis and Mode Selection

An eigenfrequency study was performed to identify the relevant acoustic modes of the reference resonator and to determine their spatial pressure distributions. For the eigenfrequency analysis, the resonator walls were treated as acoustically rigid using the Sound Hard Boundary condition,

$$\mathbf{n} \cdot \left(\frac{1}{\rho_c} \nabla p \right) = 0, \quad (4)$$

where $\mathbf{n}$ is the outward unit normal vector, and ρ_c is the complex density of the fluid domain. The eigenfrequency analysis was used to determine the resonance frequencies and corresponding acoustic pressure distributions within the frequency range of interest. The resulting mode shapes were examined to identify a suitable target mode and its nodal-line structure. The target mode was selected because its nodal-line arrangement allows the resonator to remain open in multiple radial directions, providing favorable gas-exchange characteristics, while its pressure distribution enables convenient microphone placement at the axial midpoint of the resonator. The nodal lines of the selected mode were subsequently used to determine the positions of the longitudinal slits in the resonator wall. The two acoustic modes selected for further investigation were the ν_{120} mode at 12270 Hz and the ν_{101} mode at 15235 Hz, as shown in Figure 2.

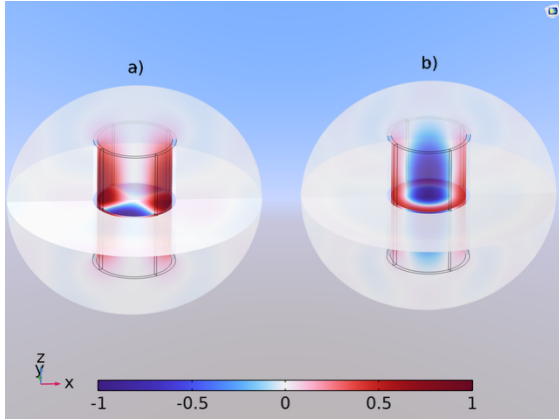


Figure 2. Normalized acoustic pressure distributions of the two eigenmodes selected for further investigation: (a) the ν_{120} mode and (b) the ν_{101} mode.

Frequency-Domain Photoacoustic Model

Following the eigenfrequency analysis, the photoacoustic response of the reference resonator was calculated using a frequency-domain study. The Pressure Acoustics, Frequency Domain interface of the Acoustics Module was used to model the propagation of the acoustically small pressure perturbations in the fluid domains.

Thermoviscous losses at the resonator walls were incorporated using the Thermoviscous Boundary Layer Impedance condition, assuming no-slip and isothermal wall conditions. This approach accounts for the viscous and thermal dissipation occurring within the acoustic boundary layers without explicitly resolving these thin layers in the computational mesh.

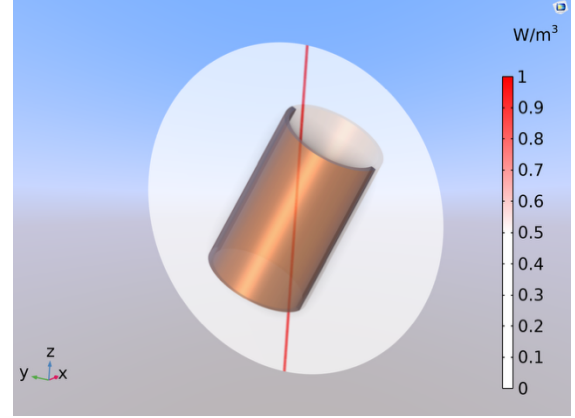


Figure 3. Spatial distribution of the Gaussian heat source used to represent the modulated optical excitation in the photoacoustic resonator.

The photoacoustic excitation was introduced using the heat source feature of the Pressure Acoustics interface, which represents the periodic heat release resulting from the absorption of intensity-modulated laser radiation. The spatial distribution of the deposited heat was modeled as a Gaussian profile, corresponding to the transverse intensity distribution of the laser beam. The volumetric heat source was defined as

$$Q_{heat} = A \cdot \exp\left(-\frac{2r^2}{w_0^2}\right), \quad (5)$$

where A is an arbitrary heat-source amplitude, r is the radial distance from the laser-beam axis, and $w_0 = 1.15$ mm is the beam radius. Since the present study focuses on the resonance frequencies and relative spectral response rather than the absolute photoacoustic signal amplitude, the simulated spectra were normalized for comparison with the experimental measurements. The spatial distribution of the heat source within the resonator is shown in Figure 3.

The simulated microphone signal was evaluated at four locations on the inner cylindrical surface of the resonator at its axial midpoint, equally spaced by 90° around the circumference. At each location, the acoustic pressure was spatially averaged over a circular surface with a radius of 0.25 mm, corresponding to the microphone inlet port. The evaluated pressure was therefore defined as

$$p(\omega) = \frac{1}{S_m} \int_{S_m} p(\mathbf{r}, \omega) dS, \quad (6)$$

where S_m denotes the microphone evaluation surface. The surface-averaged pressure was used instead of a single-point value to provide a more representative numerical approximation of the experimentally detected acoustic signal.

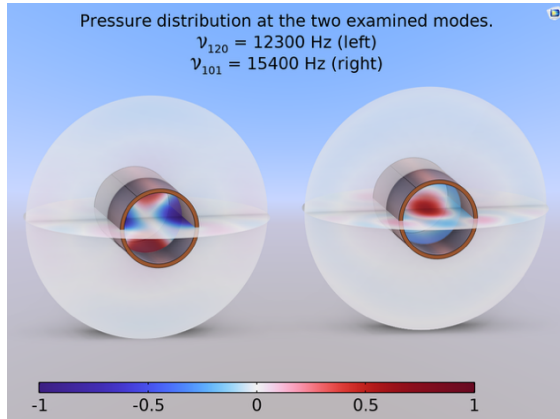


Figure 4. Normalized acoustic pressure distributions obtained from the frequency-domain photoacoustic model at the resonance frequencies corresponding to (a) the v_{120} mode and (b) the v_{101} mode.

The frequency-domain analysis confirmed that both modes selected in the eigenfrequency study can be excited by the Gaussian photoacoustic heat source. Figure 4 shows the acoustic pressure distributions obtained at the corresponding resonance frequencies. The spatial pressure patterns mirror the characteristic structures of the eigenmodes identified in the eigenfrequency analysis, confirming that both modes influence the simulated photoacoustic response.

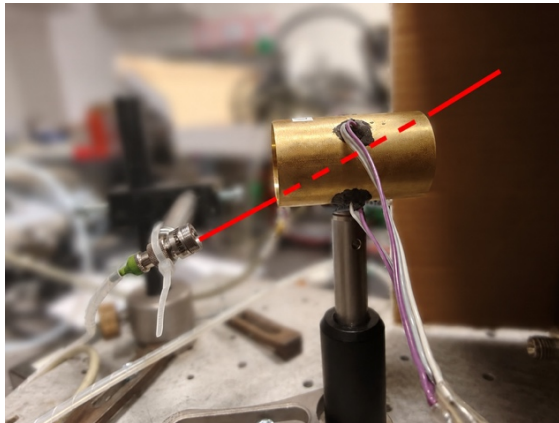


Figure 5. Experimental setup used for the validation of the reference open photoacoustic resonator. The dashed red line indicates the optical axis of the excitation laser.

Model Validation

For the experimental validation, the reference resonator was mounted in the photoacoustic measurement setup shown in Figure 5. The resonator was operated in an open configuration and exposed to ambient air, with naturally present water vapor serving as the absorbing species. Intensity-modulated laser radiation was directed along the

longitudinal axis of the resonator, as indicated in Figure 5. The photoacoustic response was recorded as the laser modulation frequency was swept over the investigated frequency range.

The frequency-domain model was validated against experimental measurements performed using the reference open photoacoustic resonator without longitudinal slits. The numerical and experimental spectra were normalized to their respective maximum amplitudes to enable comparison of the resonance frequencies and relative spectral characteristics independently of the absolute signal magnitude. The same frequency range was considered in both cases.

As shown in Figure 6, the numerical model reproduces the main resonance frequencies observed experimentally. In particular, good agreement is observed for the two primary resonances at approximately 12.3 kHz and 15.3 kHz, with only a small frequency shift between the simulated and measured spectra. A weaker spectral feature around 17.5 kHz is also captured by the model. Differences are observed at lower frequencies, most notably around 2.6 kHz, where the simulation predicts a more pronounced resonance than that observed experimentally. Nevertheless, the agreement in the frequency range that includes the modes selected for further investigation supports the use of the numerical model to study the influence of the slit-patterned geometry.

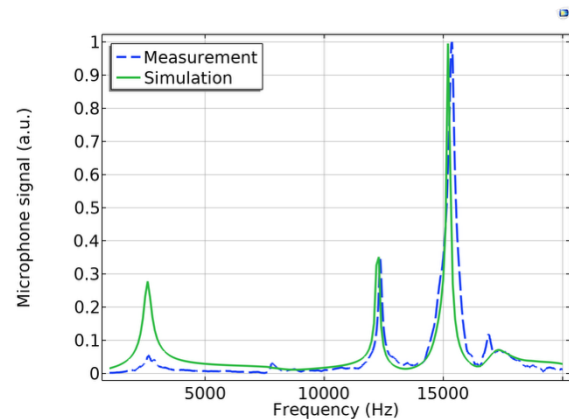


Figure 6. Comparison of the normalized simulated and measured photoacoustic spectra of the reference open resonator without longitudinal slits.

Numerical Investigation of the Slit-Patterned Design

Following validation of the reference model, the influence of the proposed slit-patterned geometry was investigated numerically. Longitudinal slits were introduced into the cylindrical resonator wall at positions corresponding to the nodal lines of the selected target mode. The slit width w_s was varied parametrically, while the remaining geometric and numerical parameters were held constant. Figure 7 shows the investigated geometries for $w_s = 0, 4, 8$,

and 12 mm, where $w_s = 0$ mm corresponds to the reference resonator without slits. Increasing the slit width progressively increases the open area connecting the resonator interior to the surrounding acoustic domain while preserving the angular positions of the openings.

The pressure distributions in Figure 8 demonstrate the slit pattern's mode-selective effect. For the target ν_{120} mode, the slits coincide with the nodal lines of the acoustic pressure field, where the pressure amplitude approaches zero. Consequently, the openings only weakly perturb the pressure distribution, and the characteristic modal structure is largely preserved. A moderate shift of the corresponding resonance frequency from approximately 12.3 kHz to 12.8 kHz is observed.

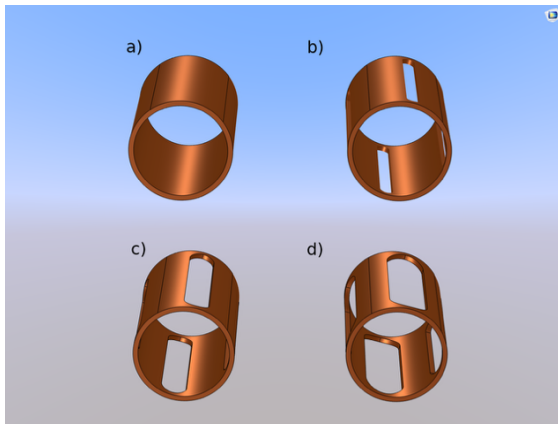


Figure 7. Geometry of the investigated open photoacoustic resonator for different slit widths: (a) $w_s = 0$ mm (reference geometry), (b) $w_s = 4$ mm, (c) $w_s = 8$ mm, and (d) $w_s = 12$ mm. The longitudinal slits are positioned along the nodal lines of the selected target mode.

In contrast, the ν_{101} mode exhibits significant acoustic pressure at the slit positions. The openings therefore establish stronger acoustic coupling between the resonator interior and the surrounding domain, allowing acoustic energy to radiate more efficiently through the slits. This behavior is visible in Figure 8(d), where a substantially stronger acoustic pressure field develops outside the resonator. The resulting increase in radiation losses reduces the competing mode's resonant response.

The physical origin of this selectivity can be understood from the complementary spatial distributions of acoustic pressure and particle velocity. At a pressure node, the acoustic pressure amplitude approaches zero while the particle-velocity amplitude is typically large. An opening positioned at such a location therefore permits oscillatory gas motion through the resonator wall without requiring a large pressure difference across the opening.

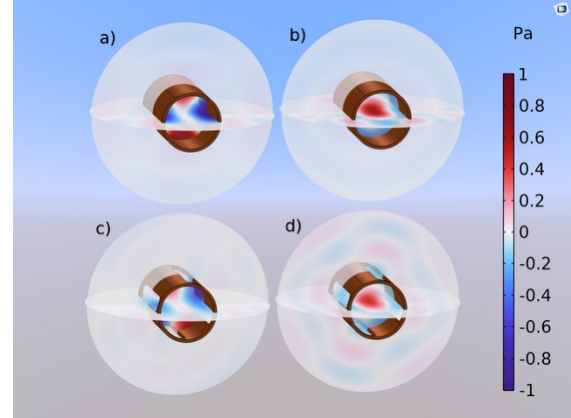


Figure 8. Normalized acoustic pressure distributions of the two investigated modes for the reference resonator (top) and the slit-patterned resonator with $w_s = 8$ mm (bottom): (a,c) ν_{120} and (b,d) ν_{101} . The corresponding resonance frequencies are 12.3, 15.4, 12.8, and 15.6 kHz for (a)-(d), respectively.

The target mode can thus accommodate the openings with relatively little perturbation to its pressure field. For the competing ν_{101} mode, however, the same openings are located in regions of appreciable acoustic pressure. The associated pressure difference drives acoustic flow through the slits and enhances radiation into the exterior domain. The slit pattern therefore introduces mode-dependent radiation losses, providing a passive mechanism for geometry-driven acoustic mode selectivity.

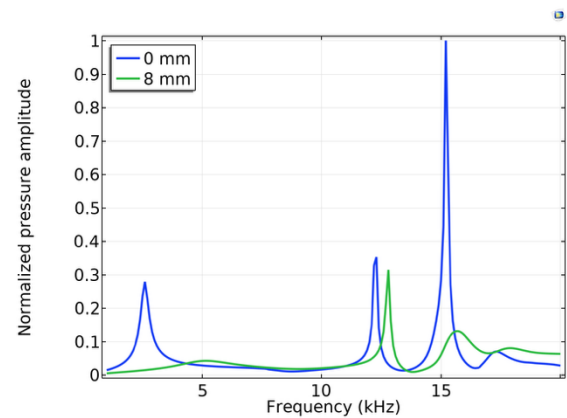


Figure 9. Simulated pressure-amplitude spectra of the reference ($w_s = 0$ mm) and slit-patterned ($w_s = 8$ mm) photoacoustic resonators. The spectra are normalized to the maximum pressure amplitude of the reference configuration.

Figure 9 shows the simulated pressure-amplitude spectra of the reference resonator and the slit-patterned configuration with $w_s = 8$ mm. The slit pattern has a strongly mode-dependent effect on the resonant response. The resonance associated with the competing mode is substantially suppressed, whereas the target mode remains clearly observable. The resonance frequencies of both modes also shift due to the changes in the acoustic boundary conditions introduced by the openings. These results

illustrate the mode-dependent effect of the slit pattern on the resonant response.

Conclusions

A nodal-line slit-patterning approach was investigated as a passive method for improving acoustic mode selectivity in an open photoacoustic resonator. A three-dimensional finite element model was developed and validated against experimental measurements of the reference open resonator, showing good agreement for the two acoustic modes of interest.

The numerical investigation of the slit-patterned resonator shows that longitudinal slits positioned along the pressure nodal lines of the target mode affect the investigated modes differently. While the target mode retains a pronounced resonant response, the competing v_{101} mode couples more strongly to the surrounding acoustic domain through the openings, resulting in increased radiation losses and a reduced resonant response.

The slit-width study further indicates that the relative amplitudes of the two modes can be controlled geometrically. These results demonstrate the potential of nodal-line slit patterning as a simple passive strategy for tailoring the modal response of open photoacoustic resonators while retaining their open-cell geometry.

Future work will focus on optimizing the slit geometry and experimentally validating the mode-selective behavior of the slit-patterned resonator.

References

- [1] P. Ganguly and T. Somasundaram, "Experiments with flowing gases in an open photoacoustic cell," *Proceedings of the Indian Academy of Sciences – Chemical Sciences*, vol. 98, no. 4, pp. 305-309, 1987.
- [2] Z. Bozóki, A. Szabó and Á. Mohácsi, "A fully opened photoacoustic resonator based system for fast response gas concentration measurements," *Sensors and Actuators B: Chemical*, vol. 147, no. 1, pp. 206-212, 2010.
- [3] J. Fekete, P. Torma and A. Szabó, "Open photoacoustic cell for concentration measurements in rapidly flowing gas.," *Photoacoustics*, vol. 30, 2023.
- [4] T. Starecki and A. Geras, "Improved open photoacoustic Helmholtz cell," *International Journal of Thermophysics*, vol. 35, no. 11, pp. 2023-2031, 2013.
- [5] T. Starecki and A. Geras, "Differential open photoacoustic Helmholtz cell," *International Journal of Thermophysics*, vol. 35, no. 12, pp. 2259-2268, 2014.
- [6] S. El-Busaidy, B. Baumann and M. Wolff, "Modelling of open photoacoustic resonators," *Photoacoustics*, vol. 18, 2020.
- [7] T. Starecki, "Influence of external acoustic noise on the operation of an open photoacoustic Helmholtz cell," *Acta Physica Polonica A*, vol. 114, no. 6A, pp. A-199–A-204, 2008.
- [8] A. Rosenczwaig, *Photoacoustics and Photoacoustic Spectroscopy*, Chichester: 1980, Wiley.
- [9] A. Miklós, P. Hess and Z. Bozóki, "Application of acoustic resonators in photoacoustic trace gas analysis," *Review of Scientific Instruments*, vol. 72, no. 4, pp. 1937-1955, 2001.

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