Evanescent Wave Quartz-enhanced Photoacoustic Spectroscopy Employing Dielectric Coated Side-polished Fibers for Sensing Applications

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Abstract: We present an all-fiber laser gas analyzer using quartz-enhanced photoacoustic spectroscopy, featuring a dielectric-coated side-polished fiber, custom quartz tuning fork, and acoustic micro-resonators, achieving over 42 times enhancement in QEPAS signal for improved detection performance.

1. Main Text

Laser Gas Analyzers (LGAs) are valuable tools for environmental monitoring, industrial process characterization, and medical diagnostics [1, 2]. Trace gas monitoring is an important cornerstone to ensure the health and sustainability of ecosystems, as well as human well-being. The continued tracking of greenhouse gases, pollutants, and other harmful substances, enables timely interventions to protect indoor and outdoor air quality and foster the development of mitigation measures for climate change and long-term sustainable industrial developments. Most LGAs have a free-space optics configuration and thus low misalignment tolerance, which limits their effectiveness, a critical factor for achieving high sensitivity and ensuring the longevity of the analyzer. Where portability is crucial e.g. agricultural or industrial settings, LGAs are often affected by mechanical vibrations. Advances in sensor technology have thus led to the development of more durable sensors for harsh environments by confining light within optical fibers or silicon photonic waveguides.

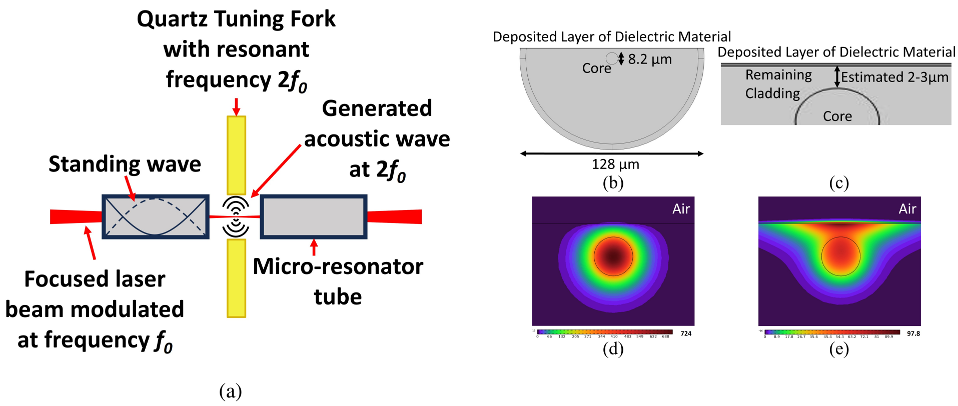
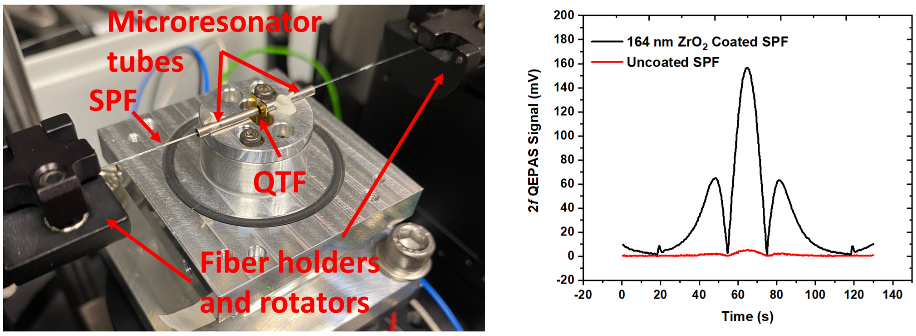


Fig. 1: (a) Schematic of QEPAS principle, the beam is aligned and focused through the microresonator tubes and QTF and the acoustic wave is generated when the target gas analyte absorbs the light, causing the QTF to vibrate and generate a piezoelectric signal, (b) Cross-sectional schematic of a side-polished fiber, (c) Schematic showing the estimated remaining cladding thickness and deposited dielectric coating, (d) Mode profile of an uncoated side-polished fiber obtained using COMSOL Multiphysics, (e) Mode profile of a dielectric coated side-polished fiber.

Quartz-enhanced photoacoustic spectroscopy (QEPAS) employs a quartz tuning fork (QTF) to detect photoacoustic waves generated by the non-radiative energy relaxation of the target gas molecules excited by a modulated laser source. In the second harmonic ($2f$) detection scheme, the probing light is wavelength modulated at half the fundamental frequency (f_{QTF}) of the QTF and focused between the two prongs of the QTF, which consequently vibrate along opposite directions within the QTF plane [3]. QEPAS does not require any optical detector and has good immunity to environmental noise. Micro-resonator tubes (mR) are acoustically coupled to the QTF to generate standing waves and enhance the acoustic waves amplitude, improving the QEPAS signal-to-noise ratio up to a few tens of times [4].

Using evanescent waves (EW) to interact with the sample analyte is a promising approach to avoid the need for sensitive alignment. For optical fibers, side-polishing [5] is a common technique to provide analyte access to the EW. The fibers used were Corning SM-28 fibers which were polished down to within a few microns of the core and had a 17 mm polished section. The EW at the polished surface of the fiber is quite weak, only being a few percent of the total intensity of the mode. To improve the performance of the EW-QEPAS sensor, we have simulated and tested various dielectric coatings on the surface of the side-polished fiber (SPF). These dielectric materials have a higher refractive index than the remaining cladding thickness of the SPF, causing the light to refract more towards the dielectric film surface, increasing the intensity of the EW. To verify that the EW intensity has increased we have measured water vapour (H_2O) and methane (CH_4) with bare SPFs and ones coated with different dielectric material thicknesses using QEPAS. We coated several SPFs with zirconium dioxide (ZrO_2) of various thicknesses from 130 to 170 nm, which were obtained from the COMSOL simulations. The thickness obtained from the simulation which gives the best enhancement is 187 nm for ZrO_2. At 1653.7 nm, the absorption wavelength of methane used in this study, the refractive index of the ZrO_2 was 1.8531. The measured QEPAS signal for the 170 nm coated fiber was over 42 times stronger than the uncoated fibers. In conclusion, covering a side-polished fiber with a high refractive index coating enhanced the evanescent field and lead to a strong photoacoustic effect in water and methane. The stronger evanescent field leads to a significant enhancement in the QEPAS signal while maintaining the advantages of fiber-based excitation.



(a) (b)

Fig. 2: (a) Image of the setup used with a dielectric coated side-polished fiber inside the microresonator tubes and between the QTF prongs, held in place by 360-degree fiber rotators on 3-axis translational stages. The fiber had a 17mm polished section which was coated with zirconium dioxide (ZrO_2). The whole setup was enclosed in a gas box which can be filled with the target gas analyte, (b) Comparison of $2f$ QEPAS spectra obtained for an uncoated and dielectric coated side-polished fibers for methane sensing at 1653.7 nm. The excitation laser source was swept over the absorption feature of the methane using a 100-second positive ramp.

References

1. J. Hodgkinson, R. P. Tatam, Optical gas sensing: A review, Measurement Science and Technology 24 (2012) 012004. doi:10.1088/0957-0233/24/1/012004.
2. E. Tütüncü, B. Mizaikoff, Cascade laser sensing concepts for advanced breath diagnostics, Analytical and Bioanalytical Chemistry 411 (9) (2018) 1679–1686. doi:10.1007/s00216-018-1509-5.
3. A. Sampaolo, P. Patimisco, M. Giglio, A. Zifarelli, H. Wu, L. Dong, V. Spagnolo, Quartz-enhanced photoacoustic spectroscopy for multi-gas detection: A Review, Analytica Chimica Acta 1202 (2022) 338894. doi:10.1016/j.aca.2021.338894.
4. P. Patimisco, A. Sampaolo, M. Giglio, S. dello Russo, V. Mackowiak, H. Rossmadl, A. Cable, F. K. Tittel, V. Spagnolo, Tuning forks with optimized geometries for quartz-enhanced photoacoustic spectroscopy, Optics Express 27 (2019) 1401–1415. doi:10.1364/oe.27.001401.
5. L. Zhuo, J. Tang, W. Zhu, H. Zheng, H. Guan, H. Lu, Y. Chen, Y. Luo, J. Zhang, Y. Zhong, J. Yu, Z. Chen, Side Polished Fiber: A Versatile Platform for Compact Fiber Devices and Sensors, Photonic Sensors 13 (2023) 230120. doi:https://doi.org/10.1007/s13320-022-0661-x.