

OPEN ACCESS

Advanced Photothermal Spectroscopy for Trace PFAS Detection

To cite this article: Yaoli Zhao *et al* 2025 *ECS Sens. Plus* 4 013401

View the [article online](#) for updates and enhancements.

You may also like

- [Highly Efficient Preconcentration of Per- and Polyfluoroalkyl Substances \(PFAS\) by Anodically Generated Shrinking Gas Bubbles](#)
Ruchiranga Ranaweera and Long Luo
- [Pulsed-Waveform Electrocatalytic Remediation of Pfas-Contaminated Aqueous Streams](#)
Brian Skinn, Huong Le, Rajeswaran Radhakrishnan et al.
- [Electrifying PFAS Cleanup: Remediation of per- and Polyfluoroalkyl Substances \(PFAS\) from Water Using Electrosorption and Electrooxidation Techniques](#)
Anaira Roman Santiago, Song Yin, Jhen-Cih Wu et al.



Advanced Photothermal Spectroscopy for Trace PFAS Detection

Yaoli Zhao,^{1,*} N. K. Jannabhatla,¹ and Thomas Thundat^{1,2,**}

¹Chemical and Biological Engineering, University at Buffalo, Buffalo, New York 14260, United States of America

²RENEW Institute, University at Buffalo, New York 14260, United States of America

The widespread industrial and consumer use of per- and polyfluoroalkyl substances (PFAS) has led to their persistent presence in the environment, driven by their robust carbon-fluorine bonds and bioaccumulative properties. This contamination poses serious health and ecological risks, making real-time, selective, and sensitive detection of PFAS critical for effective mitigation. We demonstrate a selective and sensitive detection of vapor-phase PFAS using photothermal cantilever deflection spectroscopy (PCDS), achieving a detection limit of ~30 pg. This method eliminates the need for chemically selective coatings, relying instead on the physisorption of PFAS molecules onto a bi-material microcantilever. By leveraging mid-infrared absorption and monitoring both cantilever bending and resonance frequency, PCDS enables simultaneous chemical identification and mass quantification. The technique demonstrates high selectivity in the mid-infrared fingerprint region and rapid desorption of analytes, offering significant advantages for real-time environmental monitoring and public health protection.

© 2025 The Author(s). Published on behalf of The Electrochemical Society by IOP Publishing Limited.. This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 License (CC BY, <https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted reuse of the work in any medium, provided the original work is properly cited. [DOI: 10.1149/2754-2726/ada4bc]



Manuscript submitted November 25, 2024; revised manuscript received December 28, 2024. Published January 10, 2025.

Per- and polyfluoroalkyl substances (PFAS) are a group of synthetic chemicals characterized by strong carbon-fluorine bonds, which impart high chemical and thermal stability.¹ These substances have been widely used in various industrial and consumer applications, including firefighting foams, food packaging coatings, and water-repellent products.^{2,3} The widespread use of PFAS in the manufacturing and processing of many consumer products has resulted in unprecedented environmental pollution by PFAS chemicals. Because of the strong fluorine-carbon bonds, these chemicals are chemically stable and can persist in the environment for a long time. As a result, PFAS chemicals pose a serious threat to human health and the ecosystem, making it a significant global concern. Human exposure to PFAS concentrations as low as parts-per-billion levels can result in serious health issues. Contamination by PFAS has been reported in air, water, soil, and food.⁴⁻⁷ Prenatal exposure to PFAS has been linked to reduced birth weight, possibly due to oxidative stress, endocrine disruption, and altered adipogenesis. PFAS are capable of crossing the placental barrier, contributing to developmental toxicity and increasing the risk of chronic diseases later in life.⁸ Research has established associations between PFAS exposure and several health conditions, including thyroid dysfunction, kidney disease, metabolic syndrome, and immunotoxicity.⁹⁻¹² In children, PFAS exposure has been connected to dyslipidemia, impaired vaccine response, asthma, altered renal function, and an earlier age at menarche.¹³⁻¹⁶ The global market for PFAS remediation is experiencing significant growth due to increasing regulatory pressures and public health concerns. Estimates indicate that the U.S. drinking water remediation technology sector alone is forecasted to see expenditures scaling from \$334.6 million in 2022 to \$1.1 billion by 2030,¹⁷ underscoring the urgent need for effective PFAS remediation solutions. Therefore, there is an urgent need to develop a sensor platform that can detect PFAS with high selectivity and sensitivity.

Obtaining high chemical selectivity for small molecule detection in complex environments remains challenging for many rapidly reversible chemical sensors because of the presence of interfering molecules. One way to obtain molecular specificity is by using immobilized receptors that bind selectively to the targeted analyte.^{18,19} Many currently pursued PFAS sensor platforms rely on immobilized selective coatings for PFAS absorption for detection.²⁰ These selective coatings immobilized the sensor surface,

resulting in measurable changes in the physical properties of the sensing element, for example, adsorbed mass, electrical conductivity, optical properties, etc.^{21,22}

Current sensing technologies for PFAS detection rely on immobilized selective coating.¹⁸⁻²⁰ These selective coatings immobilized the sensor surface, resulting in measurable changes in the physical properties of the sensing element, for example, adsorbed mass, electrical conductivity, optical properties, etc.^{21,22}

For example, many different variations of electrochemical sensors have been successfully demonstrated for the detection of PFAS with very high sensitivity.^{23,24} Such as silver nanoparticles modified with citrate ligands have been used for the detection of PFAS using single-particle collision electrochemistry.²⁵ Since PFAS molecules are not electroactive, attached labels are used for their detection using electrochemical techniques. Approaches using molecularly imprinted polymers (MIPs) immobilized on electrodes have shown selectivity and sensitivity. Ultrasensitive detection of PFOS using specially designed MIPs that can selectively absorb PFOS has been demonstrated by Karimian et al.²⁶ MIP-modified electrode binds to PFAS and blocks the electroactive species, for example, ferrocene, from redox reactions at the electrode. However, the use of labels remains a disadvantage for this technique. Naturally occurring oxygen in water or oxygen generated by hydrolysis is also used as a label for MIP-based electrochemical sensors.²⁷ Similarly, metal-organic frameworks (MOFs) modified electrodes have also been used for PFAS detection. Since MOFs have very large surface areas, they can capture analyte molecules to increase the adsorbate concentration by orders of magnitude. The MOF-modified microfluidic channel has been used for the detection of PFOS using changes in impedance.²⁸

Although sensors based on immobilized chemical interfaces and labels have been demonstrated to have high selectivity and sensitivity, the approach is plagued by many technical limitations such as (i) interference from non-specific adsorption, (ii) lack of high sensitivity, (iii) lack of wide dynamic range, (iv) slower response and recovery time, (v) irreproducibility and unacceptable sensor-to-sensor response variation due to patchy immobilized receptor layers (graft density variations), and (vi) irreproducibility due to aging, oxidation, and the degradation of receptors.^{29,30} The response and decay time can be longer when the adsorption energy of the target molecule on the receptor is high. This makes real-time sensing very challenging. Irreproducibility due to aging and nonuniformity in the functional coating can be a major problem for small-area sensors.^{24,31,32}

These limitations make PFAS detection techniques that do not depend on immobilized chemical interfaces or added labels especially

*Electrochemical Society Student Member.

**Electrochemical Society Fellow.

^zE-mail: yaolizha@buffalo.edu

attractive. Additionally, existing methods primarily focus on aqueous detection, often neglecting the vapor-phase pathways through which PFAS contaminants spread rapidly, particularly during manufacturing, usage, or disposal. Vapor-phase PFAS sensors are crucial for early detection and mitigation, as these compounds are frequently detected in indoor air, precipitation, and surface runoff, posing significant exposure risks.^{33–36} The lack of reliable tools for vapor-phase detection constitutes a critical research gap in the field.

Here, we report the detection of vapor phase PFAS using photothermal spectroscopy by microfabricated cantilevers. Photothermal spectroscopy using microcantilevers is an ideal platform as it combines the molecular selectivity of mid-IR spectroscopy with the high sensitivity of the cantilever beam. In the photothermal cantilever deflection spectroscopy (PCDS), the target molecules from the vapor phase physisorb on an unfunctionalized bi-material cantilever. Bi-material cantilevers are sensitive thermal sensors that can detect temperature changes with a resolution of 3–10 mK at room temperature without cooling. Therefore, a bi-material cantilever can be an extremely sensitive heat sensor capable of detecting \sim pJ of heat. Resonant excitation of the physisorbed molecules on the cantilever with mid-IR radiation generates a minute amount of heat during the non-radiative relaxation process. As a result, the bi-material cantilever undergoes bending whenever the physisorbed molecules absorb the IR radiation. The extent of cantilever bending is directly proportional to the heat generated. A plot of cantilever bending as a function of irradiation

wavelength shows the IR absorption spectrum of the adsorbed molecules. Because of the ambient temperature (\sim k_BT), a cantilever undergoes very small amplitude vibrations (Brownian motion) at its resonance frequency. It is possible to determine the mass of PFAS adsorbed on the cantilever by monitoring changes in its resonance frequency. We have simultaneously monitored the cantilever bending due to IR absorption and resonance frequency variation due to mass loading. Here, a selective and sensitive detection of vapor PFOA with a detection limit of \sim 30 pg is demonstrated.

The advantage of this technique is that it does not require any chemically selective coating to achieve molecular selectivity. Since the method is based on physisorption, the adsorbed molecules are in thermal equilibrium and desorb from the cantilever surface when the ambient concentration decreases. This technique is also very selective since mid-IR radiation is used to excite the adsorbates. Unlike the near-infrared spectrum, which is a combination of overtones and fundamental vibrations, the mid-infrared spectrum is highly selective. The mid-IR spectral region is known as the molecular fingerprint regime since the IR absorption peaks of many chemical bonds are unique in this wavelength range. In a complex mixture, the mid-IR spectrum is a combination of different absorption peaks that can be analyzed using spectral matching algorithms. Relying on the adsorbed molecules on the cantilever overcomes the major drawback of poor sensitivity faced by the traditional IR spectral techniques, which makes them unsuitable for trace detection.

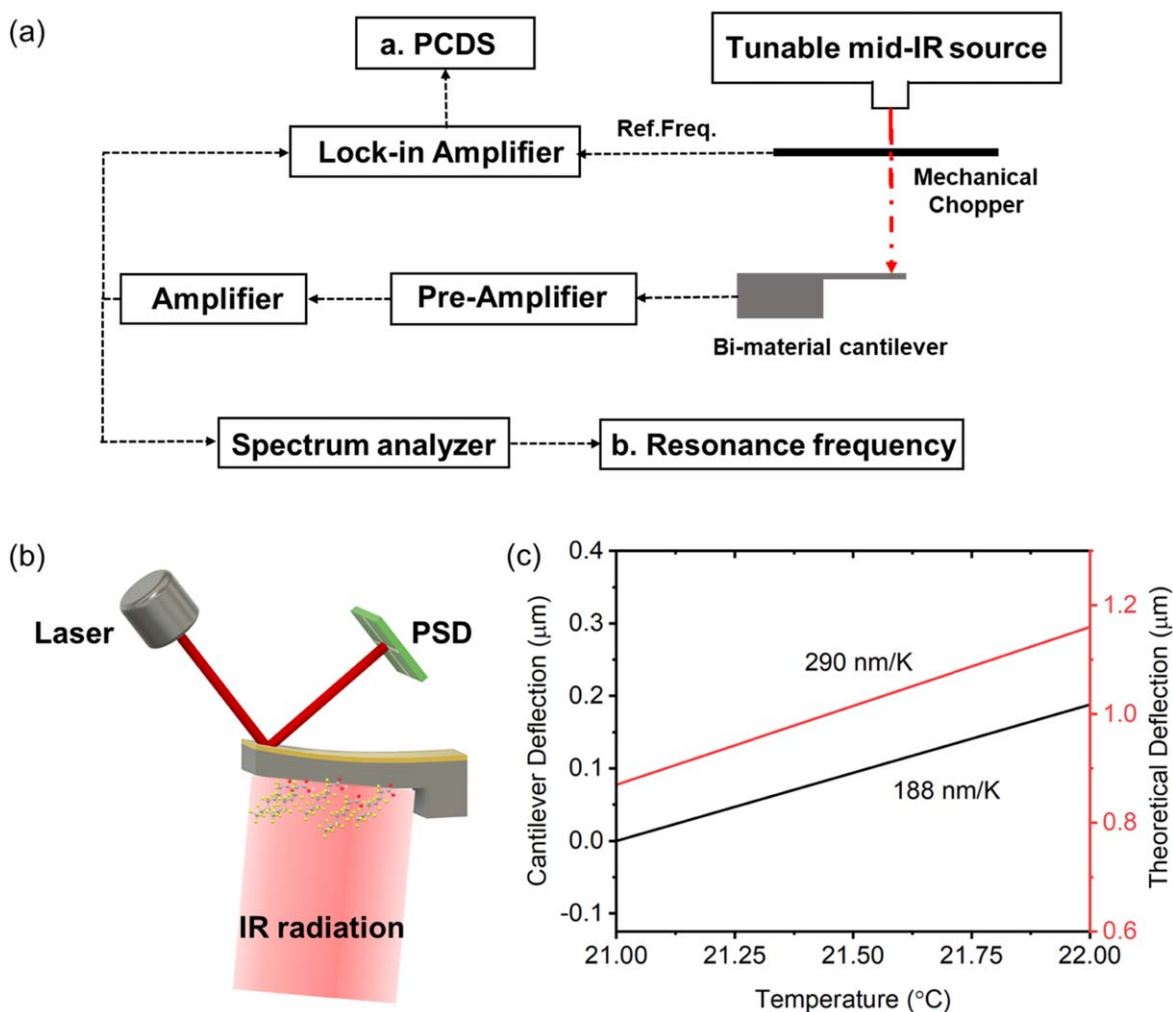


Figure 1. (a) Schematic diagram of the photothermal cantilever deflection spectroscopy (PCDS) setup, showing the simultaneous measurement of two signals: the photothermal spectrum of the molecules and the resonance frequency of the cantilever due to mass loading. (b) Schematic illustration of physisorbed molecules on a bi-material cantilever exposed to IR radiation. (c) Experimental and theoretical thermal sensitivity of the 50 nm gold-coated cantilever. The cantilever dimensions are given as $500 \mu\text{m} \times 100 \mu\text{m} \times 1 \mu\text{m}$.

Experimental

Perfluorooctanoic acid (PFOA) and 8:2 fluorotelomer alcohol (FTOH) were purchased from Sigma Aldrich and used without further purification. PFAS vapor was generated by heating the PFAS and directly exposing the cantilever to the vapor. To minimize losses due to adsorption onto tubing surfaces, the cantilever was exposed to the vapor directly, avoiding the use of tubing. All exposures were conducted in the open air within a fume hood to ensure safety and proper ventilation.

The mid-IR spectra of different samples were recorded using a customized PCDS setup constructed on a standard optical table. A tunable Quantum Cascade Laser (QCL) with wave numbers ranging from 780 cm^{-1} to 1900 cm^{-1} was employed as the MIR source (Block Engineering, LaserTuneTM), enabling comprehensive spectral analysis. The scan rate was $12\text{ cm}^{-1}\text{ s}^{-1}$. The QCL operates at an average power level of 5 mW, ensuring sufficient intensity for effective probing of the samples. To modulate the IR beam, a mechanical chopper (Scitec Instruments, model 350CD) with a frequency of 50 Hz is employed, contributing to an improved signal-to-noise ratio during data acquisition. The experimental setup is illustrated in Fig. 1a. The fabrication of the bi-material microcantilever involves depositing a 5 nm Cr adhesive layer and a 30 nm Au layer onto a commercially available silicon microcantilever using an e-beam evaporator. The choice of Au as the bi-metallic layer is justified by its high thermal diffusivity and chemical inertness, which ensures optimal spectral response data. The specific thickness of the 30 nm gold coating is intentionally chosen based on previous reports and experimental considerations.³⁷ The dimensions of the microcantilever are $500\text{ }\mu\text{m}$ in length, $100\text{ }\mu\text{m}$ in width, and $1\text{ }\mu\text{m}$ in thickness (Nanoworld, Switzerland).

Resonant excitation of adsorbed molecules using mid-IR radiation results in heat generation due to non-radiative relaxation. In PCDS arrangement, the bi-material microcantilever serves as a sensitive, broadband thermal sensor for the heat generated by the non-radiative

decay of the resonantly excited molecules. As a result, the amplitude of microcantilever bending varies sensitively as a function of the IR absorption characteristics of the physisorbed molecules on the cantilever surface when the wavelength of the IR source is tuned over the resonant wavelength range. The deflection of the bi-material silicon microcantilever is precisely measured using an optical beam deflection method. In this technique, light from a diode laser is directed onto the apex of the microcantilever, and the reflected light is detected by a position-sensitive detector (PSD), as shown in Fig. 1b. The PSD signal was read using a custom-made electronic box and was fed into a Lock-in Amplifier (Stanford Research Systems, model SR865 A) with the frequency of the mechanical chopper serving as the reference. The resonance frequency of the cantilever was monitored simultaneously from the AC part of the optical beam deflection signal from the PSD. The PSD signal is fed to a customized spectrum analyzer. The mass detection limit of the cantilever was limited by the lower resonance frequency of the cantilever. A higher-frequency cantilever provides higher sensitivity, while a lower-frequency cantilever has very high bending sensitivity.

In the PCDS experiments, the bending spectrum of the cantilever collected initially without any adsorbed PFAS molecules serves as the reference. This step was essential to account for the non-uniform intensity of the light source across the wavelength range. Moreover, this reference spectrum helps to eliminate the influence of parasitic effects, such as atmospheric absorption and the absorption by other physisorbed molecules, including water vapor. After the molecules were allowed to adsorb onto the cantilever, a new spectrum was recorded. Subtracting the reference spectrum from this new spectrum yielded a photothermal spectrum that exclusively represents the characteristics of the adsorbed molecules.

A bi-material microcantilever bends in response to temperature changes due to differential stress caused by the difference in the thermal expansion coefficients of its two constituent materials. For a microcantilever beam with a length of L and tip deflection of Z where

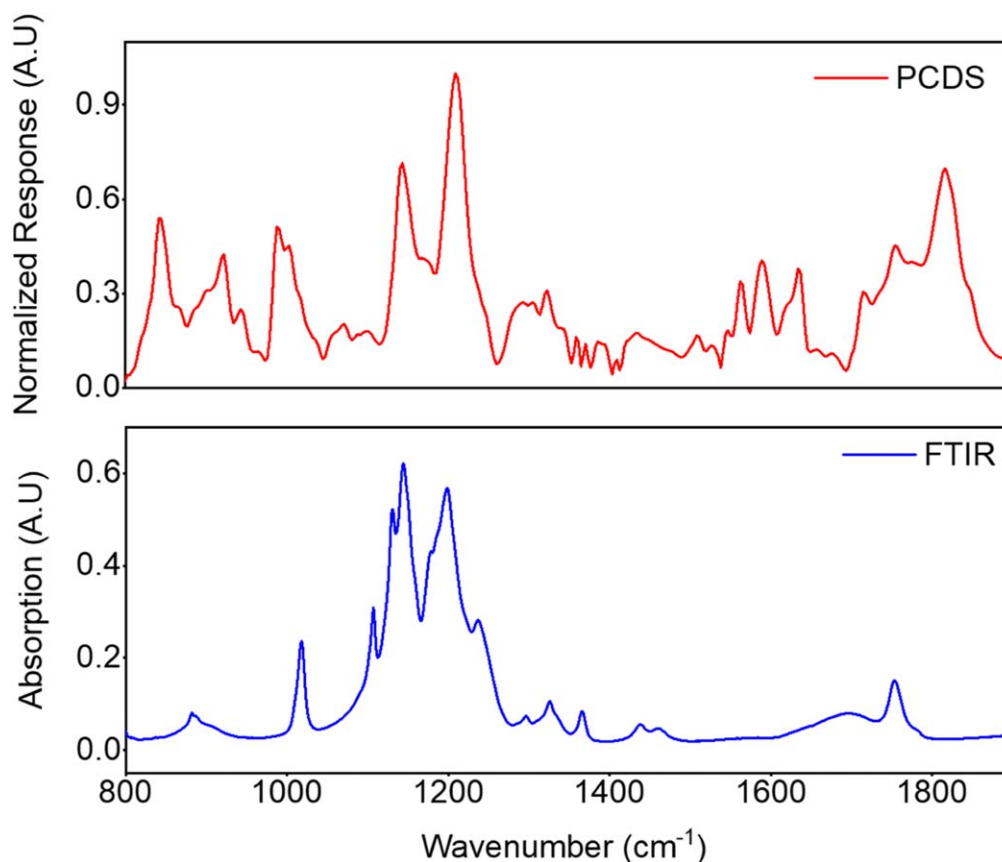


Figure 2. The photothermal spectrum of PFOA obtained with PCDS (top) and its comparison with the FTIR spectrum of PFOA (bottom).

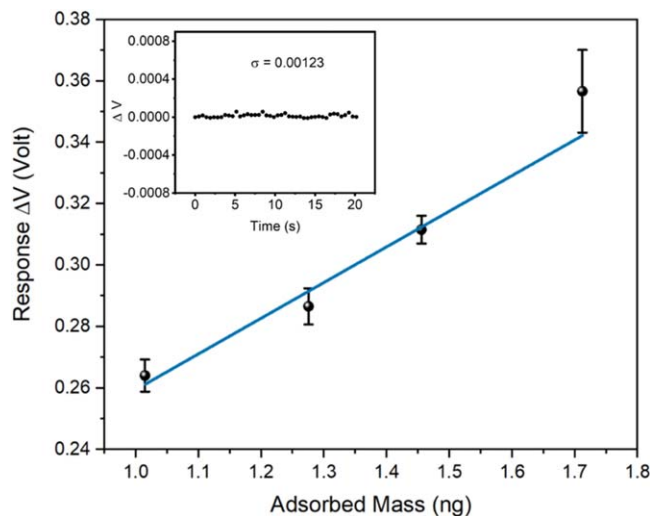


Figure 3. Calibration curve showing the photothermal cantilever deflection spectroscopy (PCDS) response as a function of the adsorbed mass of PFOA on the bi-material cantilever at a fixed wavenumber of 1200 cm^{-1} . The curve shows the dependence of the PCDS signal on the adsorbed mass. The inset shows the baseline noise level measured in the absence of PFOA adsorption. The linear fit of the calibration curve yields a sensitivity of 0.12 V ng^{-1} and a limit of detection (LOD) of 30 pg .

$(Z/L) < 0.1$, thermal sensitivity, S_T , can be estimated by Timoshenko's model.³⁸ The dimensions of the microcantilevers used in this study were $500\text{ }\mu\text{m}$ in length, $100\text{ }\mu\text{m}$ in width, and $1\text{ }\mu\text{m}$ in thickness as given by the manufacturer. Young's modulus of a Si was taken as 160 GPa . Applying these parameters, the theoretical thermal sensitivity of 290 nm K^{-1} was obtained and plotted with experimental results of 188 nm K^{-1} (5 mK nm^{-1}) as shown in Fig. 1c. The difference can be due to uncertainty in the thickness of gold and silicon layers and possibly some contribution from the Cr adhesion layer³⁹ which is not accounted for in Timoshenko's model.

Results and Discussion

In photothermal cantilever deflection spectroscopy (PCDS), the photothermal signal, measured as cantilever bending, depends on the intensity of the IR radiation. Experiments were conducted by exposing cantilevers to PFOA vapor. Figure 2 presents the PCDS spectrum of PFOA molecules physisorbed on the cantilever. This spectrum was compared with the FTIR spectrum obtained from the same sample, showing a strong correlation. The peak around 1780 cm^{-1} corresponds to the carboxylic acid stretch (COOH).⁴⁰ The peak at 1149 cm^{-1} corresponds to the CF_2 symmetric stretch,⁴¹ and the peak at 1240 cm^{-1} corresponds to the CF_3 asymmetric stretches.⁴² However, the relative peak intensities differ due to the complementary nature of the two techniques. While FTIR relies on the Beer-Lambert principle, the PCDS directly measures the heat generated by the non-radiative decay process after photon absorption. Notably, the PCDS spectrum captures all the characteristic vibrational peaks of PFOA. The resonance frequency of the bi-material cantilever decreased as a result of the physisorption of PFOA molecules on the surface of the cantilever. The observed resonance frequency difference before and after PFOA adsorption was approximately 90 Hz . The adsorbed mass was estimated as $\sim 100\text{ pg}$ from the frequencies before and after adsorption and the spring constant of the cantilever.

We have also investigated the response variation of PCDS on the adsorbed mass of PFOA on the bi-material cantilever. In these experiments, the cantilever was irradiated with 1200 cm^{-1} IR wavenumber, one of the absorption peaks of PFOA, while continuously monitoring the frequency and bending of the cantilever. The resonance frequency change provided real-time information about the adsorbed mass on the cantilever. By plotting the PCDS response as a function of the adsorbed PFOA mass, a calibration

curve was obtained as shown in Fig. 3. These results indicate that the PCDS response varies linearly with adsorbed mass. The limit of detection (LOD) is calculated as the point where the sensitivity curve intersects with the 3σ value of the baseline noise level. Here, σ is the noise level and was measured when there is no PFOA adsorbed on the bi-material cantilever as shown in the insert of Fig. 3. A linear behavior was obtained, yielding LOD ($3\sigma/m$) and sensitivity values of 30 pg and 0.12 V ng^{-1} , respectively.

The adsorbed mass of PFOA, measured simultaneously with PCDS, is limited to pico grams. A low-frequency microcantilever has a small force constant, and it is ideal for bending measurements. However, the mass sensitivity of a microcantilever increases with increasing force constant (higher frequency). As a result, bending sensitivity and mass sensitivity cannot be satisfied with the same cantilever. Using two different cantilevers, one with very high resonance frequency and the other with higher bending sensitivity, has the potential to detect and quantify the adsorbed mass over a broad range while obtaining chemical selectivity without the use of immobilized selective layers.

The sensitivity of the PCDS can be further improved by using higher-intensity light sources. The thermal sensitivity of the bi-material cantilever can be increased by optimizing the cantilever parameters, for example, surface area and the force constant. Although no pre-concentrator was used in these experiments, the use of a pre-concentrator can improve the detection limits by at least two orders of magnitude. However, the disadvantage of the pre-concentrator comes from the time delay involved in the pre-concentration step.

To evaluate the selectivity of this method, fluorotelomer alcohol (FTOH), which shares structural similarities with PFOA, was tested. The resonance frequency of the bi-material cantilever changed from 6230 Hz to 6160 Hz , corresponding to an adsorbed mass of 152 pg of FTOH. The resulting photothermal spectrum is shown in Fig. 4 and was compared with the FTIR spectrum, showing good agreement. The peak at 1055 cm^{-1} corresponds to the C-O stretch mode⁴³ of FTOH, while the peak at 1149 cm^{-1} , attributed to the CF_2 symmetric stretch, exhibits relatively low intensity.

It is important to note that infrared spectroscopy does not rely solely on identifying individual bond vibrations (e.g., C-F) but rather considers the complete spectroscopic profile across the mid-IR range. Although FTOH and PFOA share CF_2 and CF_3 functional groups, their overall infrared spectra remain distinct due to differences in chemical structure and the presence of other functional groups. Consequently, these molecules can be readily distinguished. For more complex mixtures, machine learning algorithms could further enhance classification accuracy. These findings underscore the high specificity of our sensor, enabling the detection of a broad range of targets without requiring specific surface chemistries.

To highlight the advantages of our PCDS method, Table I compares its key performance parameters with other commonly used detection techniques, including electrochemical sensors, Quartz Crystal Microbalance (QCM), and Surface Acoustic Wave (SAW) sensors. The comparison underscores the superior detection limit and high selectivity of our method, along with its reversibility, which is absent in the other techniques. As shown in Table I, the PCDS method achieves the lowest detection limit (30 pg) compared to other techniques, which range from 50 pg to 170 ng . The high selectivity of the PCDS method is attributed to its use of mid-infrared absorption spectroscopy in the molecular fingerprint region. Furthermore, the reversibility of the PCDS technique, facilitated by its reliance on physical adsorption, ensures consistent performance over repeated cycles, unlike the other methods that rely on chemically selective coatings or irreversible adsorption mechanisms.

Regeneration of the sensor is a major problem for many sensor platforms. This problem is severe for sensor platforms based on analyte adsorption on immobilized receptors and chemical interfaces. The selectivity of the sensors comes from the increased interaction energy of the analyte molecule with the receptor molecule. The increased interaction energy can originate from the multiple weak interactions (hydrogen bonds, for example) the analyte may have with the receptor molecule. However, PCDS is based on the physisorption of the target

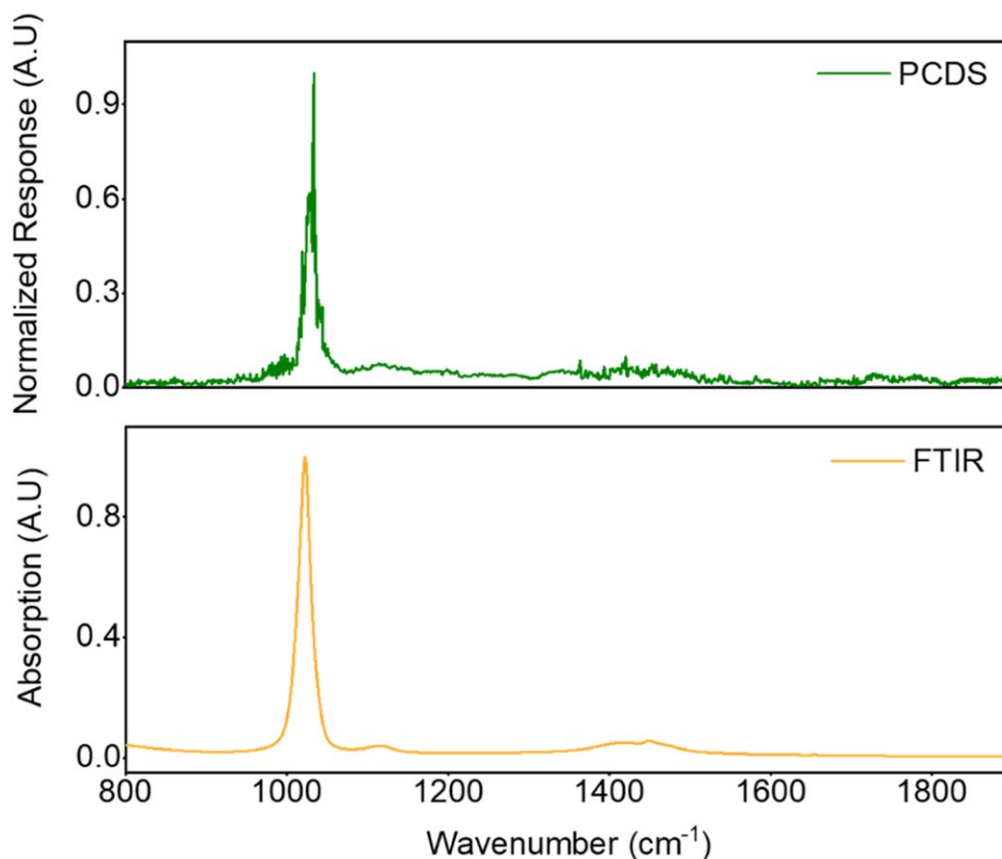


Figure 4. The photothermal spectrum of FTOH (top), and its comparison with the FTIR spectrum (bottom).

Table I. Comparison between this work and a few selected examples of current techniques reported in the literature.

Parameter	This work	Electrochemical sensors ⁴⁴	Quartz Crystal Microbalance (QCM) ⁴⁵	Surface Acoustic Wave (SAW) ⁴⁶
Lowest detection limit (LOD)	30 pg	~50–100 pg	~1–10 ng	170 ng
Selectivity	High	Moderate to High	Moderate	Moderate
Reversibility	Yes	No	No	No

molecules. Since the PFAS is physisorbed on the cantilever surface, it is in equilibrium with the vapor phase PFAS. Decreasing the PFAS concentration in the ambient results in rapid desorption of the adsorbates. Therefore, the PCDS sensor can be used for real-time detection of PFAS in the vapor phase. Therefore, the PCDS technique is an ideal sensor platform for vapor-phase PFAS chemicals.

The results presented here are based on scanning the wavelength over the entire spectral range. The main limitation of the technique is the size of the IR source. In the future, it may be possible to use globars or light-emitting diodes (LEDs) in the miniaturization of the IR source. Also, for the detection of a targeted chemical, scanning the entire wavelength window may not be necessary. It may be possible to use selected wavelengths characteristic of the absorption peaks of the targeted analyte. That can be achieved using a broadband light source, such as a globar, and filters.²⁹ Since the microcantilever has a very small thermal mass, a low-power light source is enough to obtain a photothermal spectrum. Also, the distance between the light source and the cantilever can be in the range of mm for enhanced response.

Conclusions

We have demonstrated the selective detection of PFAS chemicals in the vapor phase using a thermally sensitive microcantilever sensor via

microcantilever-based photothermal spectroscopy. Leveraging the high selectivity of molecular groups in the mid-infrared (mid-IR) fingerprint region, this method enables precise detection of small molecules with an ultralow detection limit of ~30 pg. The dual-signal strategy—combining resonance frequency variation for mass quantification with photothermal bending for chemical selectivity—provides robust capabilities without the need for immobilized selective layers. The reversibility of the physical adsorption mechanism ensures long-term usability, addressing limitations in existing methods such as coating degradation or irreversibility. Additionally, the real-time detection capability and compact sensor design highlight the potential of this technique for practical deployment in environmental monitoring and public health applications, positioning photothermal spectroscopy as a next-generation sensor platform for addressing persistent environmental contaminants like PFAS.

Acknowledgments

This work was supported by the School of Engineering and Applied Sciences (SEAS) University at Buffalo, The State University of New York, NSF Award 2226614, and SUNY Applied Materials Institute (SAMRI). We thank Kyle Leatt and Dr K. Prabakar for their help with the experiments and discussions.

ORCID

Yaoli Zhao  <https://orcid.org/0000-0002-7179-1001>

References

- Z. Wang, J. C. DeWitt, C. P. Higgins, and I. T. Cousins, *Environmental Science & Technology*, **51**, 2508 (2017).
- S. Seo, Y. Park, S. Na, J. Lee, W. Lee, and M. Kim, *Journal of Environmental Analysis, Health and Toxicology*, **27**, 1 (2024).
- J. McDonough, J. Hurst, J. Miles, and T. Pancras, *Emerging Contaminants Handbook*, **22**, 2345 (2019).
- Y. Wang, U. Munir, and Q. Huang, *Soil & Environmental Health*, **1**, 1 (2023).
- T. Schroeder, D. Bond, and J. E. Foley, *Environmental Science. Processes & Impacts*, **2**, 291 (2021).
- J. A. Hoppin, N. Kotlarz, T. deKort, J. Ng-A-Tham, A. P. Starling, J. L. Adgate, and K. Jakobsson, *Environmental Epidemiology*, **3**, 162 (2019).
- A. Ramírez Carnero, A. Lestido-Cardama, P. Vazquez Loureiro, L. Barbosa-Pereira, A. Rodríguez Bernaldo de Quirós, and R. Sendón, *Foods*, **10**, 1443 (2021).
- B. E. Blake and S. E. Fenton, *Toxicology*, **443**, 152565 (2020).
- S. E. Fenton, A. M. Ducatman, A. R. Boobis, J. C. DeWitt, C. Lau, C. A. Ng, J. S. Smith, and S. M. Roberts, *Environ. Toxicol. Chem.*, **40**, 606 (2020).
- B. E. Blake, S. M. Pinney, E. Hines, S. E. Fenton, and K. K. Ferguson, *Environ. Pollut.*, **242Pt A**, 894 (2018).
- J. W. Stanifer, H. M. Stapleton, T. Souma, A. Wittmer, X. Zhao, and L. E. Boulware, *Clinical Journal of the American Society of Nephrology*, **13**, 1479 (2018).
- G. O. Sebe, E. V. Anyaogu, A. D. A. R. C. Ntomchukwu, S. O. Oghenerhoru, and O. E. Jonathan, *Journal of Biosciences and Medicines*, **1**, 1 (2023).
- K. M. Rappazzo, E. Coffman, and E. P. Hines, *International Journal of Environmental Research and Public Health*, **14**, 691 (2017).
- O. Kuzukiran, I. Simsek, A. Filazi, and B. Yurdakok-Dikmen, *Reproductive and Developmental Toxicology 3rd edn ed.*, ch 41, p 815 (2022).
- B. E. Blake and S. E. Fenton, *Toxicology*, **443**, 152565 (2020).
- C. Gundacker et al., *Toxics*, **10**, 684 (2022).
- Bluefield. <https://bluefieldresearch.com/ns/us6-15-billion-pfas-remediation-forecast-underpinned-by-changing-regulatory-environment/>.
- N. Cennamo, G. D'Agostino, G. Porto, A. Biasiolo, C. Perri, F. Arcadio, and L. Zeni, *Sensors*, **18**, 1836 (2018).
- R. Kazemi, E. I. Potts, and J. E. Dick, *Anal. Chem.*, **92**, 10597 (2020).
- Y. Wang, S. B. Darling, and J. Chen, *ACS Appl. Mater. Interfaces*, **13**, 60789 (2021).
- D. Grieshaber, R. MacKenzie, J. Vörös, and E. Reimhult, *Sensors*, **8**, 1400 (2008).
- W. Lukosz, *Biosens. Bioelectron.*, **12**, 175 (1997).
- R. B. Clark and J. E. Dick, *Chem. Commun.*, **57**, 8121 (2021).
- M. Zhang, Y. Zhao, B. Bui, L. Tang, J. Xue, M. Chen, and W. Chen, *Crit. Rev. Anal. Chem.*, **1** (2024).
- R. Khan, D. Andreescu, M. H. Hassan, J. Ye, and S. Andreescu, *Angew. Chem. Int. Ed.*, **61**, e202209164 (2022).
- N. Karimian, A. M. Stortini, L. M. Moretto, C. Costantino, S. Bogialli, and P. Ugo, *ACS Sens.*, **3**, 1291 (2018).
- R. B. Clark and J. E. Dick, *ACS Sens.*, **5**, 3591 (2020).
- Y. H. Cheng, D. Barpaga, J. A. Soltis, V. Shutthanandan, R. Kargupta, K. S. Han, B. P. McGrail, R. K. Motkuri, S. Basuray, and S. Chatterjee, *ACS Appl. Mater. Interfaces*, **12**, 10503 (2020).
- M. Bagheri, I. Chae, D. Lee, S. Kim, and T. Thundat, *Sensors Actuators B*, **191**, 765 (2014).
- S. Kim and T. Thundat, *The Electrochemical Society Interface*, **28**, 55 (2019).
- S. Kang, K. Mathwig, and S. G. Lemay, *Lab Chip*, **12**, 1262 (2012).
- R. A. Potyrailo and V. M. Mirsky, *Chem. Rev.*, **108**, 770 (2008).
- S.-K. Kim and K. Kannan, *Environmental Science & Technology*, **41**, 8328 (2007).
- M. E. Morales-McDevitt, J. Becanova, A. Blum, T. A. Bruton, S. Vojta, M. Woodward, and R. Lohmann, *Environmental Science & Technology Letters*, **8**, 897 (2021).
- M. G. Evich et al., *Science*, **375**, eabg9065 (2022).
- M. L. Brusseau and B. Guo, *Sci. Total Environ.*, **947**, 174644 (2024).
- Y. Zhao, P. Chakraborty, Z. Meng, A. Nair, A. Goyal, and T. Thundat, *ECS Sensors Plus*, **2**, 043401 (2023).
- A. N. Sohi and P. M. Nieva, *J. Micromech. Microeng.*, **24**, 115004 (2014).
- M. Rahimi, I. Chae, J. E. Hawk, S. K. Mitra, and T. Thundat, *Sensors Actuators B*, **221**, 564 (2015).
- H. Abramczyk, B. Brozek-Pluska, J. Surmacki, J. Jablonska-Gajewicz, and R. Kordek, *J. Biophys. Chem.*, **2**, 158 (2011).
- P.-J. Huang, M. Hwangbo, Z. Chen, Y. Liu, J. Kameoka, and K.-H. Chu, *ACS Omega*, **3**, 17447 (2018).
- K. A. Carter-Fenk, K. Carter-Fenk, M. E. Fiamingo, H. C. Allen, and J. M. Herbert, *Chem. Sci.*, **12**, 8320 (2021).
- S. Burikov, T. Dolenko, S. Patsaeva, Y. Starokurov, and V. Yuzhakov, *Mol. Phys.*, **108**, 2427 (2010).
- M. Zhang, C. Hou, A. Halder, J. Ulstrup, and Q. Chi, *Biosens. Bioelectron.*, **89**, 570 (2017).
- N. L. Torad, S. Zhang, W. A. Amer, M. M. Ayad, M. Kim, J. Kim, B. Ding, X. Zhang, T. Kimura, and Y. Yamauchi, *Adv. Mater. Interfaces*, **6**, 1900849 (2019).
- W. Hao, J. Liu, M. Liu, and S.-t. He, *Proceedings of the 2014 Symposium on Piezoelectricity, Acoustic Waves, and Device Applications* 52 (2014).