News & Views Open Access

Application of suspended waveguide to enable ppb-level on-chip photonic gas sensing

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Abstract

A recent study reported a suspended chalcogenide waveguide platform that enables ppb-level molecular gas sensing on a centimetre-scale photonic chip using near-infrared photothermal spectroscopy. These results highlight the use of suspended waveguides as a promising approach to achieving ultra-sensitive, fully integrated optical gas sensors by jointly engineering light–matter interaction and on-chip thermal management.

Keywords: Photonics, Waveguide, Near-infrared photothermal spectroscopy, Gas sensing

Integrated photonic gas sensors have attracted attention as compact, low-power alternatives to bulky laboratory instruments, with potential applications ranging from environmental monitoring to medical breath analysis[1–5]. In particular, on-chip optical sensing offers high molecular selectivity, a small footprint and compatibility with large-scale fabrication, making it a key technology for next-generation miniaturised gas sensors[6–10].

Although the direct absorption of the evanescent field in integrated waveguides is the most straightforward approach to on-chip gas sensing and has long been widely investigated, its achievable sensitivity is fundamentally low for trace gas detection[11–13]. This long-standing limitation has led to increased interest in alternative strategies that can more effectively transduce weak molecular absorption into measurable optical signals. In particular, photothermal spectroscopy has attracted attention because it offers an indirect yet sensitive readout by converting absorption-induced heating into optical phase modulation[14–17]. This approach has achieved very high sensitivity in fibre-based platforms and has recently been extensively explored for on-chip implementations[18–20]. Despite this conceptual advantage, photothermal spectroscopy has so far delivered only modest gains when implemented in integrated waveguides. In the near-infrared region, most on-chip photothermal gas sensors remain confined to ppm-level sensitivity, reflecting two intrinsic challenges at the chip scale: limited absorption-induced heating due to weak light–gas interactions and rapid heat leakage into the surrounding solid cladding and substrate. Consequently, the temperature accumulation is strongly suppressed, and the full potential of photothermal sensing is yet to be unlocked in integrated photonic platforms.

A recent study by Zheng et al.[21] proposed the introduction of a suspended-chalcogenide waveguide architecture. In that study, the authors removed the conventional solid undercladding and surrounded the waveguide with air on both sides. This structural change fundamentally reshaped the optical and thermal environments experienced in guided mode. Optically, the suspended geometry dramatically increased the fraction of the evanescent field extending into the surrounding gas, directly enhancing absorption-induced heat generation.

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With a thermal conductivity more than 50 times lower than that of typical solid claddings, air acts as an effective thermal buffer, strongly suppressing the heat flow away from the waveguide. Consequently, optical heating and thermal accumulation were simultaneously enhanced within a single integrated structure.

Their experimental platform was based on a 1.2 cm-long suspended chalcogenide waveguide operating in the near-infrared region and was fabricated using complementary metal oxide semiconductor (CMOS)-compatible processes with a propagation loss of 2.6 $dB \cdot cm^{-1}$. The photothermal phase modulation induced by gas absorption was measured using a Fabry-Pérot microinterferometer naturally formed by reflections at the waveguide facets, enabling a compact and fully integrated sensing architecture. This configuration allows the photothermal response to be investigated directly on the chip while maintaining a clear separation between the pump absorption, thermal transport, and probe phase readout. Using acetylene as a model analyte, the authors demonstrated ppb-level on-chip gas sensing, achieving a detection limit of 330 ppb, a dynamic range approaching six orders of magnitude, and a subsecond response time. The corresponding noise-equivalent absorption coefficient reached 3.8×10^{-7} cm^{-1}, representing a substantial performance advance for near-infrared integrated photonic gas sensors. To the best of our knowledge, these results are among the most sensitive on-chip gas-sensing demonstrations reported to date.

The key enabler underlying this performance is neither an increase in the interaction length nor the introduction of high-Q resonant structures. Rather, it is possible owing to the use of suspended waveguides as a unified strategy to enhance the photothermal response on the chip. By removing the solid undercladding and surrounding the waveguide with air, the suspended architecture simultaneously strengthens absorption-induced heating and suppresses thermal dissipation into the substrate. Guided by a quantitative photothermal model that explicitly separates optical and thermal contributions, the authors show that the suspension yielded a fourfold increase in effective optical heating power together with a reduction of more than ten times in the effective thermal conductivity, resulting in an overall 45-fold enhancement of photothermal phase-modulation efficiency. Importantly, the thermal benefit of suspension is shown to saturate rapidly; a shallow suspension in the order of ≈10 μm is sufficient to recover most of the thermal isolation of a fully air-clad structure, establishing clear and practical design rules that balance sensitivity, mechanical robustness and fabrication complexity.

More broadly, these results coincide with a growing interest in integrated photonic platforms that extend optical functionality beyond purely electromagnetic design. Although waveguide engineering has traditionally focused on mode confinement, dispersion control and resonant enhancement, this study highlights thermal engineering as an equally powerful yet largely underexplored degree of freedom in integrated photonics. As photonic chips are increasingly developed for sensing, signal processing and light–matter interactions, their ability to quantitatively tailor heat generation and dissipation on chips can likely enable new classes of devices that were previously difficult to realise. Suspended-waveguide photothermal spectroscopy offers a general and scalable strategy for translating concepts from bulk and fibre-based systems into compact, ultrasensitive photonic sensor chips.

Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The author declares no competing interests.

Received: 05 February 2026 Revised: 08 April 2026 Accepted: 08 April 2026
Published online: 27 April 2026

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