Photothermal Common-Path Interferometry for Trace Gas Detection

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Abstract: Photothermal common-path interferometry is used for sensitive infrared gas spectroscopy. Numerical modeling of the effect is validated by experimental results. The method enables compact sensor systems that operate largely independent of the actual excitation wavelength.

1. Photothermal infrared spectroscopy

The maturing of mid-infrared (MIR) interband and quantum cascade laser sources has boosted the comprehensive application of infrared laser spectroscopy as a tool for substance detection, characterization and quantification. Although mid-infrared detection is co-evolving with MIR light sources and applications, detector noise remains a bottleneck limiting the sensitivity of spectroscopic systems. This motivates the use of photothermal methods that rely on measurement of temperature changes in the sample - contrary to detecting a fractional loss of power at the excitation wavelength. These methods, especially photoacoustics, beam deflection or thermal lens spectroscopy, exhibit high detection sensitivities without the need for long absorption paths, provide scalability with excitation power and allow for largely wavelength-independent operation [1]. Recently, optically read-out photothermal methods have come into focus with applications in trace gas detection [2] or concentration monitoring [3].

2. Gas detection by photothermal common-path interferometry

In this work, photothermal common-path interferometry (PCI), a method primarily used for absorption spectroscopy in high-power laser optics [4], is considered for gas sensing. The principle is based on a thermal lens caused by an excitation beam absorbed by the sampled, symmetrically engulfed by a larger, low-power probe beam, typically in the visible or near-infrared. The partial disturbance in the probe beam causes an interference pattern superimposed onto the undisturbed beam profile. Figure 1a) shows a sketch of the basic measurement setup. By modulation of the excitation beam and phase sensitive lock-in measurement of the interference amplitude, sensitive absorption measurements are achieved in a small sample volume, i.e. the overlap region of the beams. The detection scheme allows for compact setups with few optical elements and is virtually offset-free since the modulation is only generated in the interaction zone, whereas photoacoustic systems often are prone to wall signals. This further stresses a key ability of photothermal methods: measuring zero signal when no absorbing analyte is present.

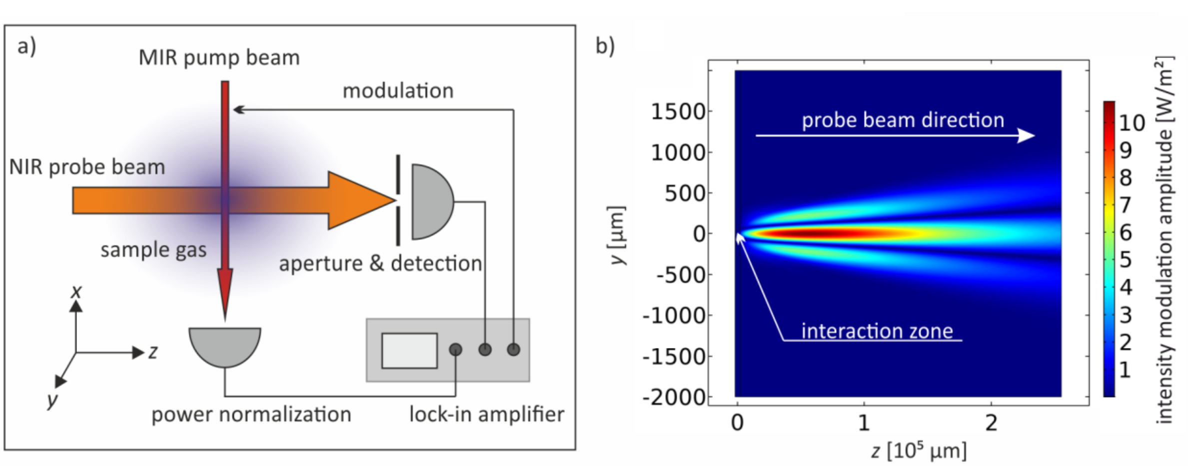

Figure 1a) PCI gas measurement setup scheme. b) Simulated evolution of intensity modulation of the probe beam cross section caused by the thermal lens (“interaction zone”) in the gas sample.

A numerical model of the two-beam interaction and subsequent probe beam propagation was developed. Figure 1b) shows a cross section of the intensity modulation profile imprinted onto the probe beam by the thermal lens. The model results closely match the spatial pattern of experimental data. Figure 2a) shows measured intensity modulation of the probe beam, geometrically resolved by scanning a single mode fiber aperture perpendicularly to the probe beam direction, compared to simulated values. The measurement was performed at a modulation frequency of 385 Hz.

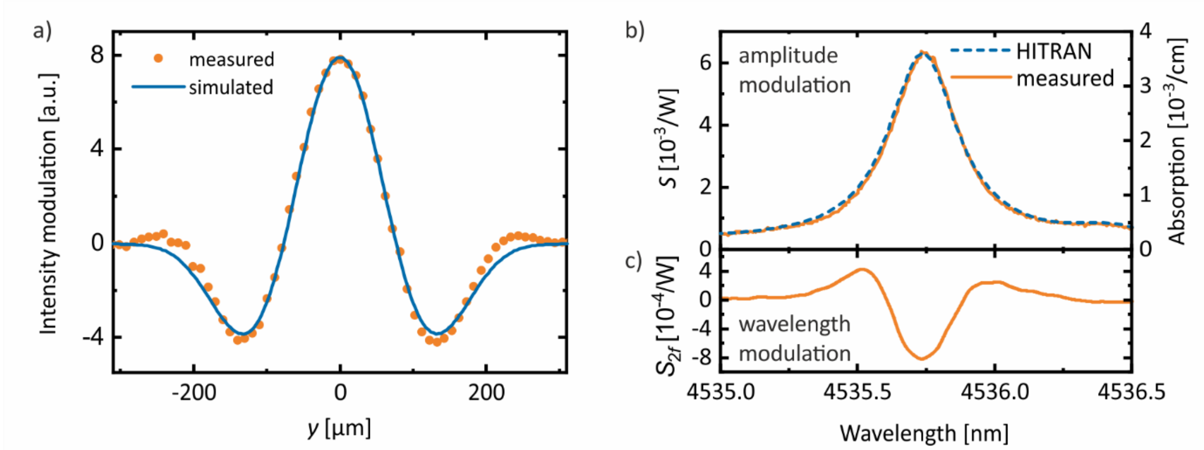

Figure 2: Experimental results compared to theoretical values. a) Signal geometry: simulated cross section of the intensity modulation compared to the lock-in signal measured through a single mode fiber vertically scanned over the probe beam behind the interaction zone. (b): Infrared spectroscopy by PCI. Signal of 50 ppm of N_2O in air (top) measured with an amplitude modulated QCL compared to simulated absorption based on HITRAN data. The bottom plot shows the corresponding $2f$-PCI signal obtained by wavelength modulation of the QCL.

Spectroscopic application of PCI for trace gas detection was demonstrated by measuring the absorption signal of N_2O around 4535.7 nm, as shown in Figure 2b). A quantum cascade laser (QCL) was intensity modulated and tuned over the absorption. The excitation beam was crossed with the probe beam in a sample cell filled with 50 ppm N_2O in humidified natural air. The PCI signal S is given by

$$S = \frac{U_{\mathrm{AC}}}{U_{\mathrm{DC}} \cdot P_{\mathrm{e}}},$$

where U_{AC} is the signal modulation and U_{DC} the average DC signal measured by the probe beam detector, while P_{e} is the maximum excitation power. Comparison to HITRAN simulation data shows good agreement. The scheme is equally suited for wavelength modulation spectroscopy. The bottom inset of Figure 2b) shows the $2f$-signal recorded by a wavelength modulated sweep of the QCL. For the measurements, the QCL delivered a cw optical power of about 20 mW.

A normalized noise equivalent absorption detection limit of 1.4×10^{-6} $\mathrm{Wcm^{-1}Hz^{-1/2}}$ was determined using ambient moisture (H_2O) as a model gas with 300 mW excitation power at a near infrared wavelength of 1120.42 nm and an integration time constant of 100 ms.

3. Conclusion and outlook

Combining high sensitivity at low integration times with a compact system footprint and very small sample volumes, gas detection by photothermal common-path interferometry is a promising tool for real time monitoring of low substance concentration. The sensor operation independent of the excitation source allows for the combination with wider tunable and more powerful infrared sources, bridging the gap to real trace gas detection. Medical as well as environmental applications will benefit from the favorable combination of detection properties.

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