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Continuous-filtering Vernier spectroscopy

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Abstract

Continuous-filtering Vernier spectroscopy (CF-VS) is a laser-based detection technique that combines the broad spectral coverage of an optical frequency comb (OFC) with the enhanced interaction length provided by an optical cavity. The resonances of the cavity filter the OFC to a small group of comb modes that probe the transitions of the species present in the cavity. Controlling cavity resonances allows for a fast scanning of the selected comb modes across the full bandwidth of the comb. CF-VS delivers high detection sensitivity through its immunity to the frequency-to-amplitude-noise conversion. Previous works have shown the capability of CF-VS to perform sensitive and broadband measurements of multiple species in both the near-infrared (NIR) and the mid-infrared (MIR) regions. Those implementations required high-bandwidth stabilization via feedback to the comb sources, which resulted in bulky setups and complex operations. Moreover, they provided acquisition rates up to 20 Hz, limited by the mechanical design. Besides, the target species were measured under static conditions — CF-VS had not yet been employed to monitor any time-dependent processes.

The goal of the thesis was to address these issues. In the first project, we used CF-VS based on an Er: fiber comb to measure consecutive spectra of H₂O and OH with 25 ms time resolution in a premixed flame whose fuel/air equivalence ratio was modulated with a square wave to simulate temporal perturbations. The concentrations of both species were retrieved with percent level precision, and their temporal profiles were repeatable in each modulation cycle. The steady-state concentrations were in good agreement with a static flame simulator. This work was the first demonstration of CF-VS and cavity-enhanced comb-based spectroscopy with ms time resolution.

In the second project, we implemented a new design of CF-VS that uses a compact Er: fiber comb and a custom-made moving aperture. This removes the requirement for high-bandwidth stabilization and allows acquisition rates up to 100 Hz. To verify these capabilities, we measured CO₂ and CH₄ spectra in two spectral ranges. We developed a simple model to account for the influence of the high scanning speed above the adiabatic limit on the absorption signal.

The last project aimed to implement a robust and compact CF-VS spectrometer in the MIR region. For that, we improved an existing MIR source based on difference frequency generation (DFG) using a low-noise Yb: fiber pump, delay stabilization, and a novel polarization-maintaining silicon crystal fiber. The MIR comb uses a soliton generated in the fiber as the seed for DFG. We characterized the soliton using the pump laser. The wide tuning range of the soliton allows the idler to emit in the 2.7–4.2 μm range with high brightness. The MIR comb has a simple delay stabilization and a fixed zero-offset frequency and was successfully implemented to measure high-resolution and precision spectra of CH₂I using a comb-resolved Fourier transform spectrometer. Finally, we used the source to perform CF-VS by measuring CH₄ spectra at around 3.3 μm. We showed that a single-shot spectrum could be successfully retrieved under the robust operation in the fingerprint regime.

Keywords

spectroscopy, spectrometer, laser, optical frequency comb, optical cavity, NIR, MIR, flame, robust, time resolution, spectrum

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