Mutually Injection Locked Gain Switched Optical Frequency Combs for Dual Comb Spectroscopy of H_2S

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Abstract: Application of two mutually injection-locked gain-switched optical frequency combs for near-infrared spectroscopy of H_2S in air is demonstrated. The high phase correlation between OFCs allows measurement sensitivities of 740 ppmv using a compact, flexible device.

1. Introduction

In recent decades, optical frequency combs (OFCs) providing a number of equally spaced, phase coherent narrow spectral lines have been used in state-of-the-art gas-phase laser (absorption) spectroscopy [1]. Gain switching of commercially available semiconductor lasers, as an OFC generation technique, has gained prominence due to its simplicity and flexibility [2]. Some shortcomings associated with the gain switching as a technique to generate OFCs can be overcome by using external injection. In recent years, dual comb (DC) spectroscopy (DCS) [3] has become a popular technique to overcome many of the constraints of conventional Fourier transform spectroscopy through the simplification of the receiver, offering high precision and fast acquisition times [3]. A crucial factor for DCS is high frequency accuracy and high spectral resolution, which can be achieved using extremely low linewidth OFCs [4]. However, such OFCs can be expensive and bulky [4]. In this paper, high-frequency accuracy and high-resolution is provided through achieving a high level of phase coherence between the gain-switched (GS) OFCs. The two GS OFCs are phase and free spectral range (FSR) locked via optical injection locking with a single semiconductor based external cavity laser (ECL). The employment of such mutual injection locking of the two OFCs, leads to a stable and narrow linewidth radio frequency (RF) beat tone spectrum, which enables its use in DCS of H_2S in air in the near infrared region at ~1574.5 nm. In addition, the outlined DC architecture lends itself to the possibility of being photonically integrated, enabling the realization of a compact and cost-efficient DC interrogator.

2. Experimental Setup

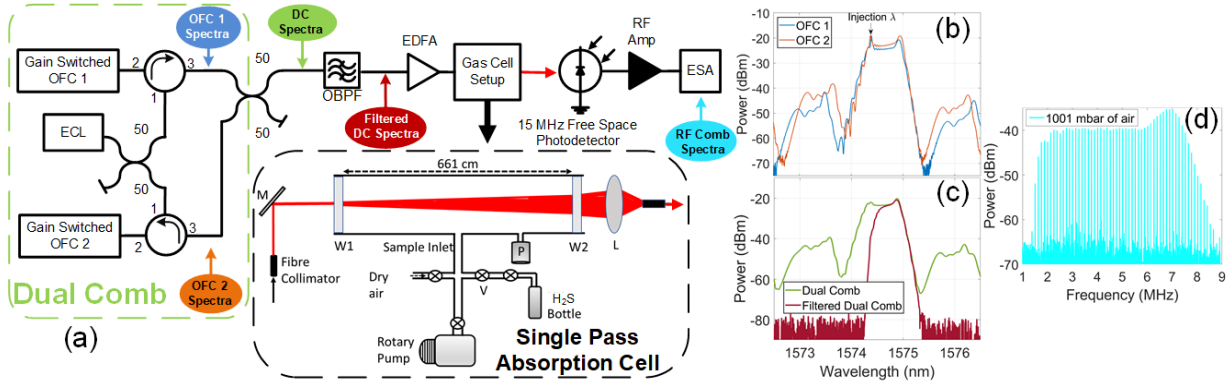

Figure 1: (a) DCS setup used to detect H_2S in the near-infrared. Optical spectra taken at the points indicated in the experimental setup; (b) OFC1 (blue line) and OFC2 (orange line) and (c) DC output before (green line) and after the optical bandpass filter (OBPF) (red line). (d) Background RF beat tone spectrum taken with the ESA. W1, W2: optical windows; L: Achromatic lens; P: Absolute pressure sensor; V: valve; M: mirror.

The experimental setup used for the DCS of H_2S is illustrated in Fig. 1(a). It comprises two Fabry-Pérot (FP) (slave) lasers, with thresholds of 11.9 and 12.7 mA respectively. The FP lasers are biased at 6.1 and 8.5 mA respectively with their corresponding temperatures being maintained at 23.3 and 23.9 ºC. Both FPs are GS using amplified RF sine waves of 27 dBm at frequencies of 1.250000 and 1.250125 GHz respectively [2]. The individual OFCs are mutually injection locked using a single ECL acting as a common master laser providing FSR and phase locking to both slave lasers. The wavelength of the master laser is optimized to 1574.376 nm, shown in Fig. 1(b), in order to create broad asymmetric OFCs which will maximize the number of comb lines generating unique RF beat tones. The optical spectra of the generated mutually injection locked OFCs are observed at the points indicated by the ovals in Fig. 1(a), with the aid of a 2.5 GHz resolution optical spectrum analyzer (OSA); the respective spectra are

illustrated in Fig. 1(b). The two OFCs are combined with a 3-dB coupler and the optical spectrum of the resulting DC is shown in Fig. 1(c). The DC is passed through an optical bandpass filter (OBPF) in order to remove tones lower than the master laser wavelength. This ensures any beating on the detector between the two OFCs will generate a unique frequency. The OBPF output is shown in Fig. 1(c). After the OBPF, the DC is amplified by an Erbium doped fibre amplifier (EDFA) to compensate for losses incurred in the single pass absorption cell. The signal from the EDFA is guided into the cell with a beam steering mirror. The static gas cell is a stainless steel pipe (diameter 10 cm) with a length of d = (661.0 ± 0.1) cm, sealed with two optical windows at either end [5]. The cell has access ports for evacuation and sample introduction. The light exiting the cell is imaged onto a 15 MHz InGaAs photodetector (Thorlabs PDA10D) with the aid of an achromatic lens (focal length 7 cm). The tones from the DC yield an RF spectrum, illustrated in Fig. 1(d), consisting of unambiguously assignable RF beat tones separated by 125 kHz and captured on an electrical spectrum analyzer (ESA).

2. Measurement Results with H_2S

All H_2S experiments are carried out at near atmospheric pressure (~1000 mbar); in the field, the cell could simply be replaced by an open path approach. Before each measurement, a background spectrum, I_0, is taken with the chamber filled with dry air, the resulting RF spectrum is shown in Fig. 1(d). Subsequently, the chamber is evacuated and H_2S at different pressures is introduced. Dry air is then introduced at atmospheric pressure to mimic a quasi-open atmosphere condition. The transmitted intensity, I, is then recorded after 30 mins waiting time in order to attain thermodynamic equilibrium for the gas mixture. The resulting RF spectra are illustrated in Fig. 2(a) for 10.2 (orange), 15.9 (yellow) and 25.0 (purple) mbar of H_2S in air. Evident in the RF spectrum is an absorption at 2.5 MHz caused by the main ro-vibrational absorption line of H_2S located at 1574.55 nm. A zoom of this region is shown in Fig. 2(b). The absorption coefficients, $(I_0/I\text{-}1)d^{-1}$, for each RF beat tone are plotted against a wavelength scale in Fig. 2(c) along with the integrated line intensities from the HITRAN database [6]. Evident are absorption features at 1574.62, 1574.70, and 1574.86 nm, whose positions correspond to H_2S absorption lines in the HITRAN database. The maximum uncertainty in the calculated mixing ratio is 21.7 % and the sensitivity is estimated to be is 740 ± 161 ppmv. Detection below the lower explosion limit (LEL) of 40 ppTv is possible with good selectivity.

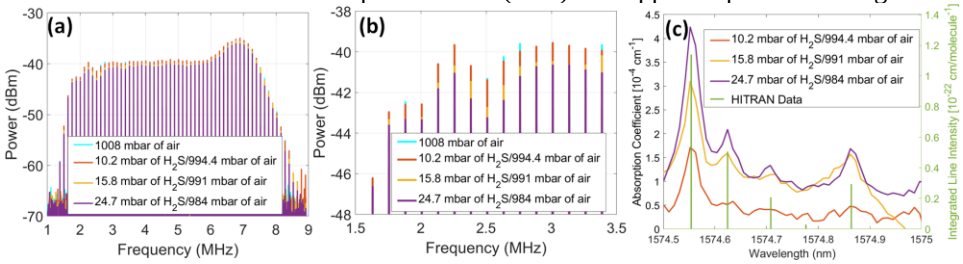

Figure 2: (a) Resulting RF beat tone spectra for varying pressures of the target gas. (b) Zoom of the RF spectra showing absorption at 2.5 MHz. (c) Calculated absorption coefficients for each spectrum along with the integrated line intensities from the HITRAN database.

3. Conclusion

This paper demonstrates the use of mutually coherent gain switched OFCs for DCS of H_2S in air. The DC consisting of one OFC with 1.250000 GHz FSR and the other with 1.250000 GHz FSR and 125 kHz detuning enabled the measurement of four absorption features of H_2S over a range of 0.5 nm in agreement with data from the HITRAN database. The measurements provided a sensitivity of 740 ± 161 ppmv which allows for detection below the LEL. The common master generates a highly phase coherent DC which provides high frequency accuracy and spectral resolution. The use of FP (slave) lasers offers the potential to sense multiple gases in the near-infrared using the same interrogator architecture through the tuning of the master laser to another set of FP modes. As the proposed DC architecture is potentially integrable, and the receiver has a low bandwidth; a compact, robust and commercially viable gas sensor for field applications is feasible based on these proof-of-principle measurements.

4. References

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