

Tuned Sideband Diode Laser Absorption Spectroscopy

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Abstract

Tunable Diode Laser Absorption Spectroscopy allows for real-time, non-intrusive gas detection and concentration measurements. In conventional implementations it relies on determining the laser frequency during tuning, which hampers precise reconstruction of the absorption line due to non-linear effects. In this work, a method utilizing precisely controlled, frequency varying first order sidebands to probe an absorption line is demonstrated. A calibration procedure for determining the frequency modulation depth is introduced and implemented experimentally. The results demonstrate good agreement between simulation and measurement, highlighting the potential of sideband-sweeping for implementing accurate laser absorption spectroscopy.

Keywords: TDLAS, frequency modulation, sidebands sweeping, gas concentration

Introduction

Tunable Diode Laser Absorption Spectroscopy (TDLAS) is a well-established, non-invasive technique for detecting trace gases with high sensitivity and selectivity [1]. It uses the frequency tuning capabilities of a diode laser to probe molecular absorption features by adjusting either the injection current or the operating temperature of the laser. The resulting absorption signal is described by the Beer–Lambert–Bouguer law, which directly relates the attenuation of light intensity to the molecular number density along the optical path [2].

The accurate reconstruction of the absorption line is critical for determining gas concentration in TDLAS setups. However, the mechanisms of frequency tuning via injection current and thermal modulation are inherently complex, making precise determination of the laser frequency during tuning challenging [3]. One approach to address this issue involves using the line shape signal generated by frequency modulation (FM) as an absolute frequency reference [4]. In this method, the zero-crossing point of the line shape signal corresponds to the molecular resonance, while the two extrema on either side are symmetrically positioned at a distance equal to the modulation frequency from the resonance, effectively forming a frequency scale. Nevertheless, the resolution and accuracy of this calibration technique are limited by factors such as the characteristics of the phase shifter and nonlinearities introduced by intensity variations and it requires the use of photodiodes fast enough to resolve the sideband modulation.

Here, instead of directly tuning the laser frequency via the injection current the sideband frequencies of the laser are used to probe the absorption feature. These sidebands are generated through frequency modulation, producing two spectral components symmetrically positioned on either side of the carrier frequency [5]. The frequency offset of each sideband from the carrier is precisely equal to the modulation frequency. By varying this modulation frequency, the sidebands can be accurately tuned across the molecular absorption line without altering the carrier frequency itself. This method enables precise frequency control of the probing light and eliminates the need for high-speed photodiodes and heterodyne detection schemes. Instead, a standard photodiode is sufficient to measure the attenuation of the modulated light caused by sideband absorption.

Methodology

Laser frequency modulation has been extensively used and described for numerous applications [5]. When modulating the laser's central frequency ω , the resulting electric field of the emitted light can be expressed as $E = E_0 e^{i(\omega t + \beta \sin \Omega t)}$, where β is the modulation depth and Ω is the modulation frequency. This expression can be expanded using Bessel functions to:

$$E \approx E_0 [j_0(\beta) e^{i\omega t} + j_1(\beta) e^{i(\omega+\Omega)t} - j_1(\beta) e^{i(\omega-\Omega)t}], \quad (1)$$

with $j_0(\beta)$ and $j_1(\beta)$ being the zero order and first order Bessel functions, respectively, representing the amplitude contribution of the carrier and first sidebands for modulation

depths β sufficiently small to allow for disregarding higher order sidebands. When the modulation depth is small, the majority of the optical power is distributed among the carrier and the first-order sidebands, while the contribution from higher-order sidebands becomes negligible, i.e. $j_0^2(\beta) + 2j_1^2(\beta) \approx 1$. The method proposed here is demonstrated using a molecular oxygen absorption line as illustrated in Fig. 1 exhibiting a half width at half maximum (HWHM) width of 1.51 GHz at 1 bar and 296 K.

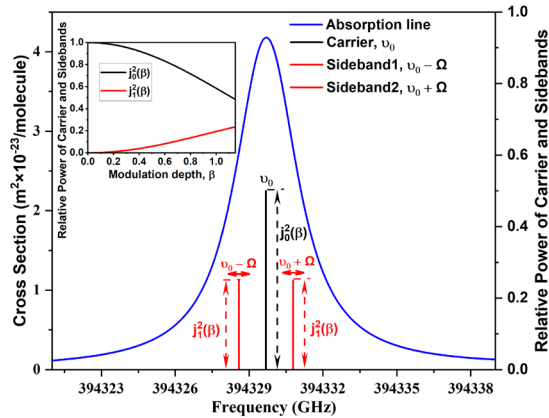


Fig. 1: Illustration of an absorption line (blue) at 1 bar and 296 K and the laser frequency components: the carrier is locked at the resonance center, while two first order sidebands are symmetrically positioned on either side of the carrier frequency.

As the modulation frequency increases, the sidebands are tuned away from the resonance, transitioning from regions of strong absorption to those with lower absorption. Consequently, the total absorption decreases, and the transmitted optical power increases. As the modulation depth increases, the relative power in the first order sidebands increases, while the relative power in the carrier decreases. This redistribution of power results in reduced total absorption, leading to an increase in transmitted optical power. The change in transmitted power is captured using a standard photodiode without the need for signal demodulation. Due to the precise frequency control of the probing sidebands, the detected photodiode signal can be analytically modeled using the Beer–Lambert–Bouguer law. This enables accurate reconstruction of the absorption line, facilitating precise quantification of the gas concentration.

Results

The calibration of the modulation depth can be performed by sweeping the modulation power while keeping the modulation frequency fixed and recording the corresponding photodiode signal. Increasing the modulation power results

in a higher photodiode signal in the presence of target gas molecules. To enable accurate calibration, the photodiode signal under unmodulated conditions must also be recorded. After calibration, the absorbance $\alpha(\nu_0)$ and $\alpha(\nu_0 - \Omega)$ corresponding to each swept modulation frequency can be determined. As shown in Fig. 2, the simulated absorbance and the experimentally measured values for different modulation frequencies exhibit good agreement. Notably, the determination of absorbance is independent of the total laser power P_0 , which eliminates the influence of power fluctuations caused by laser aging or contamination. This enhances the stability and accuracy of the proposed method further.

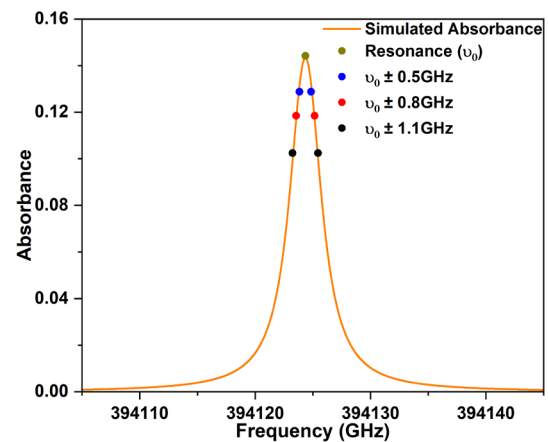


Fig. 2: Comparison between simulated and measured absorbance. The simulation is under known conditions: number density is 2.599×10^{25} molecules/m³, the effective absorption length is 1.05 m, temperature is 296 K and pressure is 1 bar.

References

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