Suppressing the influence of optical fringes in dispersion spectroscopy

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Abstract—In this letter we show that in chirped laser dispersion spectroscopy (CLaDS) a significant reduction of parasitic optical fringes can be achieved. Good agreement between theoretical model and experimental data is demonstrated. Such a fringe reduction capability makes CLaDS technique a good candidate for field applications in which long-term accuracy is critical.

Laser spectroscopy is a powerful tool in various fields including fundamental research [1], environmental monitoring [2-3], industrial process control [4-5], or medical diagnostics [6]. With sensitivity enhancement schemes based on optical paths increase using e.g. multi-pass cells and by targeting the strongest ro-vibrational transitions with mid-IR lasers, high precision is achievable with sensitivities down to ppmv (parts per million by volume) and ppbv (parts per billion by volume) levels [7]. However, in many applications achieving long-term stability and measurement accuracy of a spectrometer it represents a significant challenge. This is especially difficult in field applications when environmental conditions can strongly affect system performance and periodic re-calibration is often complicated and/or inconvenient. In many cases the detection limit of concentration measurements is usually limited by optical fringes resulting from spurious reflections and scattering of laser light from optical surfaces. In practice, these interference features are present in every system even when all transmissive elements are tilted and have an antireflective (AR) coating. The transmission of such etalons contributes to the measurement as a parasitic signal that, unlike random noise, cannot be removed by averaging. Thus the opto-mechanical instability of the system results in variations of the etalons and leads to drifts in the output signal that worsens the long-term performance of a spectrometer. In spectroscopic detection techniques in which spectral information is encoded in the intensity of light (e.g. direct laser absorption spectroscopy DLAS or wavelength modulation spectroscopy WMS), optical fringes can only be suppressed by careful optical alignment or efficient AR coatings. More flexibility is provided when gas concentration is retrieved from the detection of a phase of light, as it is performed in dispersion techniques. An example of such a capability is shown in this letter, where we present the suppression of optical fringes using recently developed chirped laser dispersion spectroscopy (CLaDS).

Detecting molecular concentration through optical dispersion sensing is an alternative method to more common absorption measurements [8-11]. Detecting small refractive index changes is often more challenging, but several techniques exist that provide access to molecular dispersion information. The most established ones include FM spectroscopy [9] and NICE-OHMS [12], with the latter known for its record sensitivities achievable in well-controlled laboratory conditions. Recently, we have introduced CLaDS – a robust dispersion based technique for gas sensing [13, 14], which offers a variety of unique detection capabilities and can be used in field conditions. In CLaDS, dispersion is probed with a dual-color laser beam that creates a heterodyne beatnote signal in the square-law photodetector used as a receiver. As the laser wavelength is chirped across the target transition, molecular dispersion manifests itself as a variation of the beatnote frequency (more details can be found in Ref. [13]). CLaDS provides several advantages over other spectroscopic techniques including: immunity of the CLaDS signal amplitude to the fluctuations of light intensity [3], or linear dependence of the CLaDS signal amplitude on molecular concentration [15]. Despite many new measurement capabilities CLaDS (similarly to other methods based on coherent laser sources) suffers from optical fringes that affect the phase of light and create periodic fringe structures also in the dispersion spectrum.

In CLaDS, however, it is possible to reduce the influence of optical fringes. Fundamentally, CLaDS is a differential technique in which dispersion affects both frequency components of a dual-color beam. The CLaDS signal is created due to a different phase shift than those two components experience. Therefore any periodic fringe structure in the dispersion spectrum can be effectively suppressed if the spacing between frequency components is set to an integer multiplication of the fringe free

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spectral range FSR (see Fig. 1). A similar reduction of fringe visibility was previously reported for FM spectroscopy [16] and for NICE-OHMS (the concept of fringe immune distances) [12], and showed considerable improvements in spectrometer performance.

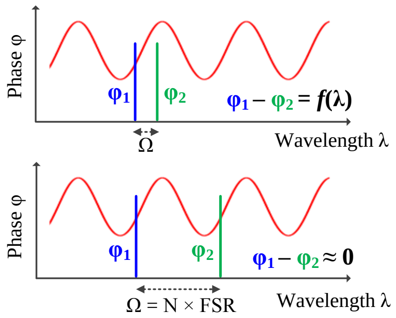

Fig. 1. The concept of fringe reduction in CLaDS: two frequencies used for dispersion sensing are spaced by Ω. In CLaDS dispersion signal is created due to different phase shift than they experience. When Ω is set as integer multiplication of fringe FSR, etalon affects the phase of both frequencies in exactly the same way, thus CLaDS dispersion signal will not be generated.

The suppression of fringe signal visibility in CLaDS was experimentally verified using the setup shown in Fig. 2. The laser source was a telecom distributed feed-back (DFB) laser diode (LD) operating at approximately 1548 nm with its frequency chirped using a triangular modulation of the injection current. Laser light was passed through a dual parallel Mach-Zehnder modulator which, when properly biased, created a single side-band signal with a frequency spacing Ω. A dual-color beam was subsequently sent through an unbalanced Mach-Zehnder interferometer constructed with two identical 3dB couplers and a fiber patchcord in one arm, which simulated an optical etalon with FSR of ~160MHz. The light transmitted through the unbalanced interferometer was focused onto a fast InGaAs photodetector. An RF beatnote was analyzed with a spectrum analyzer that retrieved the dispersion profile through frequency demodulation at the carrier frequency Ω. Additionally, since the CLaDS technique besides measuring the sample dispersion allows for simultaneous detection of sample transmission using amplitude demodulation (AM) [13], the etalon transmission spectrum was measured as well.

Both dispersion and absorption signals measured with CLaDS for four different frequency spacing Ω are shown in Fig. 3. The dispersion signal amplitude as well as frequency axes in both graphs were corrected for a non-constant chirp rate during the scan. One can clearly observe that the selection of Ω strongly affects the amplitude of measured fringes in the dispersion spectrum. With Ω being close to integer multiplication of FSR (13×160MHz=2080MHz≈2075MHz) the fringe is strongly suppressed. At the same time, the fringe signal in the transmission spectrum is substantial and even at its smallest level (obtained for Ω = 2000MHz = 12.5×FSR) is still comparable with the direct laser absorption spectroscopy (DLAS) measurement performed for the same etalon.

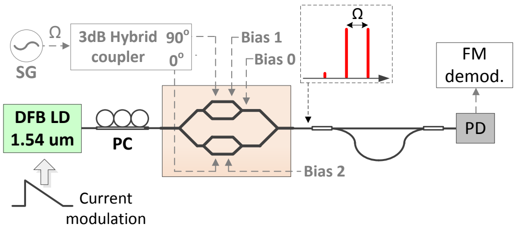

Fig. 2. Experimental setup (SG – signal generator, PC – polarization controller, PD – photodiode).

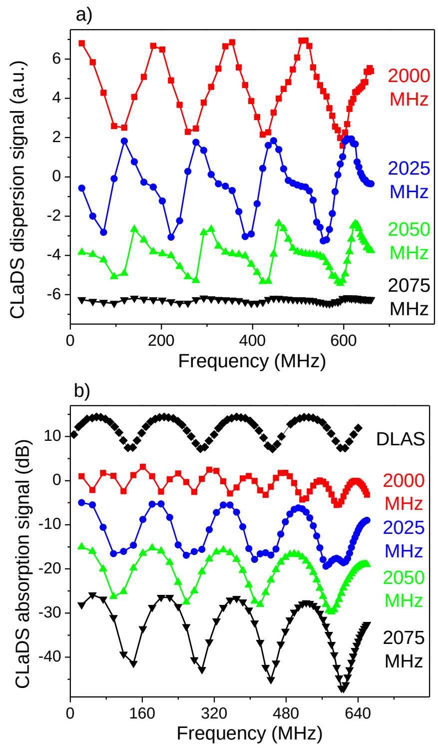

Fig. 3. CLaDS dispersion and absorption spectra of an optical etalon recorded for different frequency spacing Ω using FM and AM demodulation, respectively. DLAS spectrum was measured using a tunable laser source and a high-resolution optical spectrum analyzer.

The experimental results in Fig. 3 are in good agreement with the CLaDS modeling presented in Fig. 4. The modeling was performed using CLaDS theory in Ref. [13] and the sample was simulated as an ideal Fabry-Perot etalon with FSR=160MHz. The same model was used to show other potential benefits of the presented fringe-suppression mechanism. The inset of Fig. 5 shows an example of a simulated transmission spectrum of 500ppbv N_2O around 2207.62 cm^{-1}, at reduced pressure of 50Torr and for optical length of 10m. We assumed the presence of a 20-cm-long optical etalon (FSR =750 MHz in air). These are realistic assumptions: few hundreds ppbv is a typical ambient N_2O concentration, a 10m optical path can be easily obtained using a multi-pass cell and a similar etalon was present in previous CLaDS instruments due to a poor AR coating on the acousto-optical modulator [3, 17] (similar fringes can also be created when a multi-pass cell is used [18]).

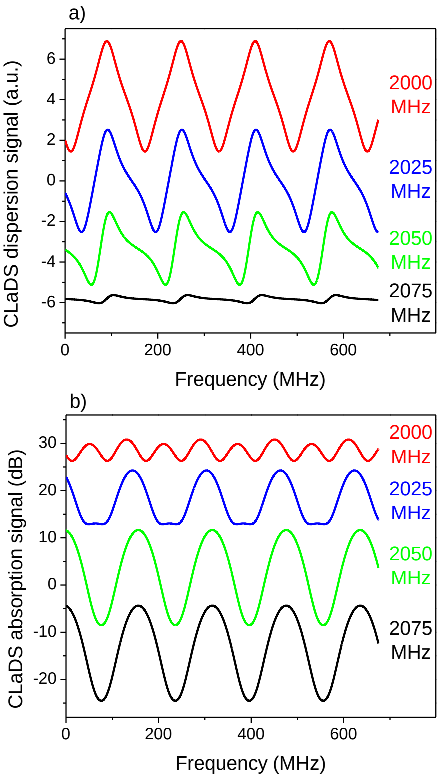

Fig. 4. CLaDS dispersion (a) and absorption (b) signals modeled for optical etalon used in our experiments.

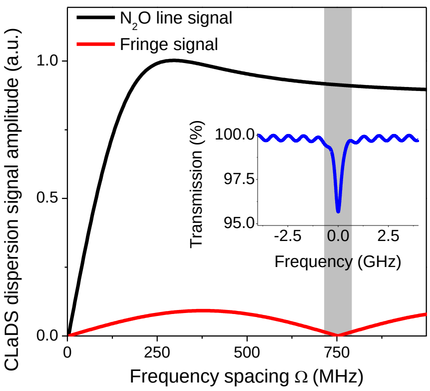

Fig. 5. Amplitude of a CLaDS dispersion signal for N_2O transition at 2207.62cm^{-1} (black) and amplitude of an optical fringe pattern from an etalon (red) plotted for different values of frequency spacing Ω. The grey area indicates Ω that provides the strongest suppression of fringe amplitude with only ~10% reduction in N_2O signal amplitude. Inset: A transmission spectrum of the N_2O line affected by the etalon used in the simulation.

Figure 5 shows amplitude simulation of a CLaDS dispersion signal as a function of frequency spacing Ω for both N_2O and fringe spectrum. It is clear that when the N_2O signal amplitude is maximized and Ω≈300MHz, the influence of a fringe signal is significant. Therefore, in order to suppress the fringe influence and improve long-term stability, the sensor should be operated at Ω≈750MHz. In these conditions for the price of an approximately 10% loss in the signal amplitude, a significant reduction of the optical fringe can be achieved with respect to Ω≈300 MHz.

In this letter we have shown that with the CLaDS technique a significant reduction of parasitic optical fringes can be achieved through optimization of frequency spacing Ω. A good agreement between the theoretical model and experimental data has been demonstrated. The main limitation of the presented technique is that it guarantees fringe reduction only for one specific etalon with a known FSR. However, with a proper design of the optical system that uses consistent equidistant placement of optical elements, one can minimize the probability of optical fringing with other FSRs than the dominant one (the concept of fringe immune distances). Such a fringe reduction capability, together with previously shown immunity of the CLaDS signal to intensity variations [13] and linearity of CLaDS amplitude to molecular concentration [15] makes the CLaDS technique a good candidate for field applications in which long-term accuracy is critical.

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