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Methane detection of chirped laser dispersion spectroscopy using DSB-SC modulation

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ABSTRACT

This paper discusses the use of double-sideband suppressed-carrier (DSB-SC) modulation and radio frequency mixer as phase detector to extract phase information for methane detection in chirped laser dispersion spectroscopy (CLaDS). The 1.66 μm light from narrow-linewidth laser was modulated by electro-optic modulator (EOM) working on DSB-SC mode. These two sidebands passed through gas chamber and formed interference on photodetector. The phase change from gas absorption in beating signal can be extracted by using passive RF mixer with another input as reference signal which is achieved by doubling RF drive signal of EOM. In RF mixer, two inputs with identical frequency but various phase shift corresponds to DC bias voltage variation of output. The phase change is proportional to refractive index change and can be referred to gas concentration by using Kramers-Kronig relations. The advantage of phase sensitive CLaDS is wide dynamic range for gas detection. It compensates the deficiency of wavelength modulation spectroscopy (WMS) on high concentration circumstances. And the passive scheme pushes the system requirement to the lowest level.

Keywords: Chirped laser dispersion spectroscopy, double-sideband suppressed-carrier, passive demodulation, methane sensor.

1. INTRODUCTION

For many years, tunable-diode-laser (TDL) absorption spectroscopy has been widely used on absorption-based gas measurement. Because of its simplicity, accuracy and relatively simple interpretation of the results, it has been discovered many advantages on measurement of various gas parameters. Temperature [1], concentration [2] and pressure measurements have been reported and most of them relied on absorption line detection which is governed by Beer-Lambert law. However, at low-absorption situation, the low signal-to-noise ratio (SNR) make direct-absorption spectroscopy hard to get an accurate and convinced measurement. To improve SNR, wavelength-modulation spectroscopy (WMS) [3,4] has been put forward on sensitive species detection. More than scanning the part section of spectrum, WMS employs additional rapid sinusoidal current injection to modulate laser wavelength. The interaction between the rapidly modulating wavelength and a nonlinear absorption feature brings about harmonic components in the detector signal, which can be isolated with lock-in amplifier. Generally, the first (1f) and second (2f) harmonic component are attached importance because of their strong dependences on either laser properties or gas properties.

Both of direct-absorption mechanism and WMS are based on Beer-Lambert law. The intrinsic property of Beer-Lambert law limits its use in more challenging applications: nonlinear under strong absorption and volatile to optical power fluctuation. [5] Starting from Kramers-Kronig law, chirped laser dispersion spectroscopy (CLaDS) offers an alternative solution for trace gas detection. [6] By measuring the optical dispersion occurring in the vicinity of molecular absorption of light, it is immune to intensity variations, and provide linear response within the full range of accessible concentration levels.

In CLaDS, the measurement of refractive index changes from frequency [6-9] and phase [10,11] detection give rise to the molecular concentration. Frequency CLaDS requires high-performance real time spectrum analyzer to extract frequency variation, and high-speed laser ramp modulation to proportionally fit the slop of output signals. On the contrary, phase CLaDS only needs a phase extractor to obtain phase signals. By implementing heterodyne scheme, the phase shift can be extracted through lock-in amplifier (LIA). In the previous work of phase CLaDS, a double-sideband suppressed-carrier (DSB-SC) method has been proposed to solve the model accuracy error, that two sidebands from EOM with same frequency as well as phase. [11] The phase out of the extraction becomes rather simple. However, the

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synchronization of radio frequency (RF) between EOM and LIA in DSB-SC scheme has some shortcomings especially with high frequency modulation. In this paper, we present an improved scheme which passively uses the RF mixer as phase extractor and RF multiplier as reference. In contrast to phase CLaDS with LIA, RF mixer and multiplier are passive devices of analog circuits bringing the advantage of simplified implementation and integration. The phase shift is directly expressed by bias voltage from output of RF mixer which reduces the requirement of data acquisition (DAQ) system. In this paper, the prototype has been validated in a simple and crude gas chamber without temperature control, which is far from optimal.

2. DISPERSION DETECTION THEORY

In physics, photons at certain frequency which rightly match the energy gap of the gas molecules are significantly absorbed. Methane molecules have four fundamental vibrations. Especially in the near-infrared region, it exists the combination band of $\nu_2 + 2\nu_3$ (around 1.33μm) and overtone band $2\nu_3$ (around 1.66μm). The overtone band absorbs 10 times more infrared energy.

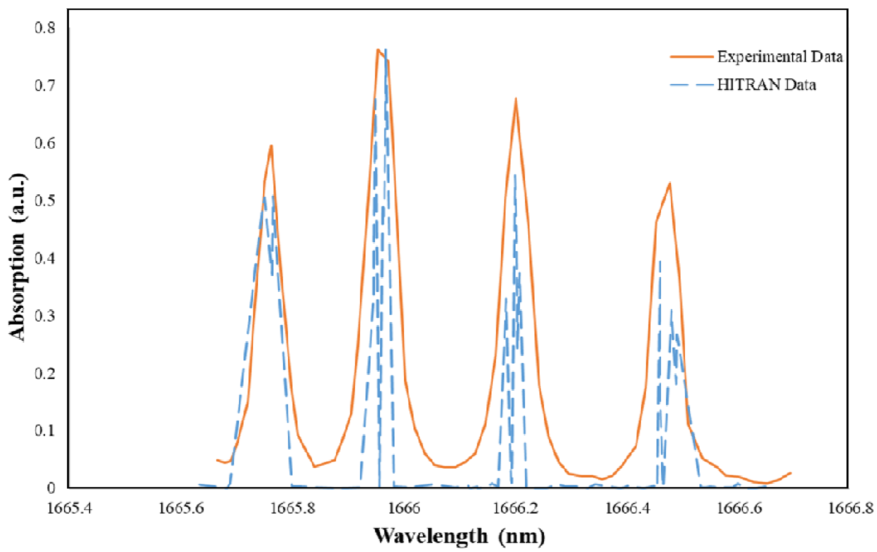

Figure 1. Methane direct-absorption spectrum from HITRAN database and experiment in this paper.

In figure 1, from a given database of HITRAN, the absorption line of methane around 1.66μm has been confirmed. The line of 1.6659 μm has been chosen as center wavelength in this experiment. Based on Kramers-Kronig relations, the optical dispersion can be rewritten in a form of refractive index associated with absorption coefficient at certain frequency. [6]

$$n(\omega) = n_0 + s_n \frac{\omega_c - \omega}{(\omega_c - \omega)^2 + \frac{\triangle\nu^2}{4}},$$

where s_n is a parameter determined by the gas concentration and absorption line shape. $\triangle\nu$ is the FWHM of line shape and ω_c is the central optical angular frequency. [2]

In this paper, we used heterodyne scheme of DSB-SC to retrieve the phase shift from gas concentration. Figure 2 shows DSB-SC modulation in oscilloscope and optical spectrum analyzer (OSA). The light from laser diode with angular frequency ω_0 is modulated by an EOM at radio frequency Ω. Through tuning the bias voltage of EOM, DSB-SC is formed as two sidebands ω_0+Ω and ω_0-Ω. These two sidebands scan the absorption line by tuning the center frequency ω_0. By simply matching the Ω with absorption linewidth, phase difference between two sidebands can be written into a form of refractive index changes,

$$\varphi_{\omega_0} = \varphi_{\omega_0 - \Omega} - \varphi_{\omega_0 + \Omega} = \frac{\omega_0 \cdot L}{c}[n(\omega_0 - \Omega) - n(\omega_0 + \Omega)],$$

where L is the length of gas chamber. And it can be measured at photodetector by square law.

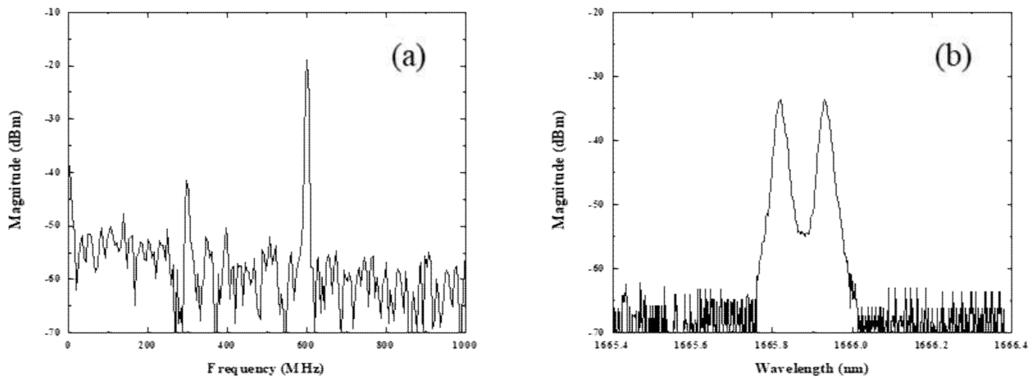

Figure 2. Visualization of DSB-SC modulation. (a) 300 MHz RF generates 600MHz beating signals in oscilloscope. (b) 6 GHz RF generates two sidebands in OSA. The value of RF is chosen under the limitation of oscilloscope (DC - 1 GHz) and OSA (0.01 nm resolution).

Most phase CLaDS system uses LIA in the measurement as phase detector. In DSB-SC modulation, the beating frequency becomes 2Ω which lets RF signal Ω cannot be directly used in demodulation. The RF multiplier is the simplest way to deliver the high-quality doubled frequency with low phase noise. Incorporating with RF mixer, the demodulation scheme becomes concise, effective and passive.

The crucial issue of passive scheme is noise level control. [12] The process of multiplication involves phase noise inevitably, like doubling the frequency degrades the input signal by 6dB, And the imbalanced circuits in mixer also bring about DC offset and mixer-induced phase shift.

The noise of RF multiplier can be mitigated by lowering conversion loss and maximizing input signal power. Because both phase noise and amplitude noise are strongly dependent on the level of the input signal, with high conversion efficiency, the noise level can be decreased. And for the DC offset, it can be minimized by applying an appropriate DC bias to the output port and selecting a mixer with high isolation. Meanwhile, the mixer-induced phase shift can be eliminated by calibrating the mixer before use.

3. DSB-SC AND PASSIVE DEMODULATION REALIZATION

1.6659 μm light emitted from laser diode (EP1665-9-DM-B01-FA) is modulated by a ramp signal for scanning over the selected absorption line. The linewidth of laser diode is 3 MHz. The arrangement of the proposed experimental schematic is shown in Fig. 3. The ramp signal has set to be 10Hz triangular wave. An EOM (Mach-10 081) has been driven at frequency 690 MHz by a RF generator (SG6000). By gently tuning the bias voltage to 4.2 V, double sidebands have been generated with interval of 1380 MHz. And the same frequency has be formed by feeding 690 MHz RF signal into a RF multiplier (ZX90-2-11+). The gas chamber was selected to be 3D printed that can be embedded into an adjustable U-benches with APC connector (FBP-C-FC). The optical path length within the measurement of gas cell is 5cm.

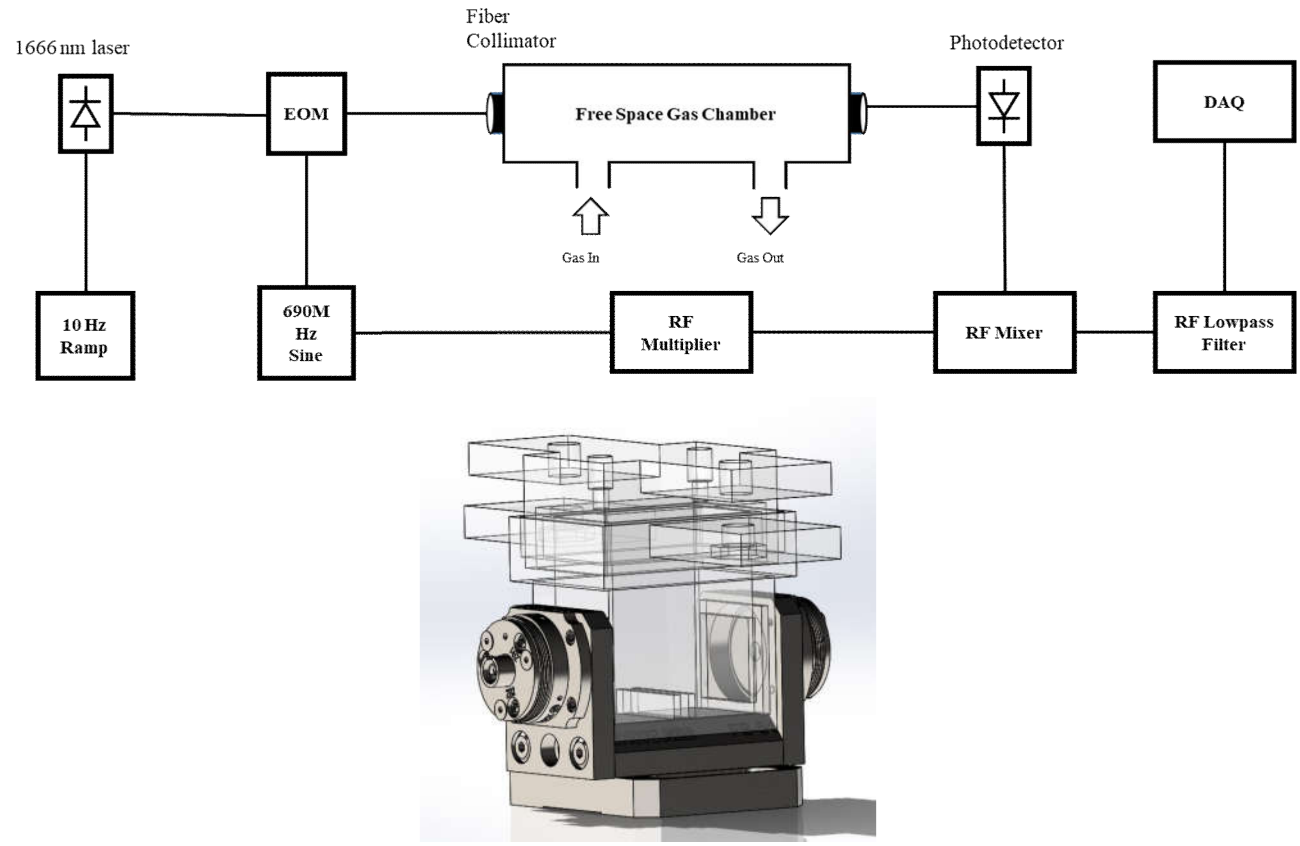

Figure 3. Schematic of phase chirped laser dispersion spectroscopy with DSB-SC and passive demodulation and 3D printed gas cell.

After passing through the gas cell, the light is captured by a high-speed InGaAs fiber-coupled amplified photodetector (FPD310-FC-NIR) with 1 MHz - 1.5 GHz bandwidth. The up limit 1.5 GHz restricted the range of radio frequency that sending into EOM. From previous research [7], the maximum CLaDS signal located at 730 MHz which push us to choose the parameters close to this value.

Two sidebands from EOM meet at photodetector generating the beating frequency 1380 MHz due to square law. And the beating signal is mixed with a reference RF signal from multiplier by RF mixer (ZX05-C24-S+). The phase related output is denoised by a lowpass RF filter (SLP-1.9+). To mitigate the phase noise in RF mixer, the calibration process also needs to be done before experiment. By manually setting the phase difference of two RF signals in the function generator, the mixer-induced phase shift has been recorded. And with pure nitrogen filled in the gas cell, the DC output has been known as to compensate the DC offset of RF mixer.

4. METHANE MEASUREMENT OF PHASE DETECTION

The gas cell is filled with standard methane in different concentration diluted by nitrogen. Under 1 atm pressure, methane concentration is controlled by flowmeter that communicated by serious port. Figure 4 shows the phase signals in one ramp scanning period and result of several high concentration circumstances.

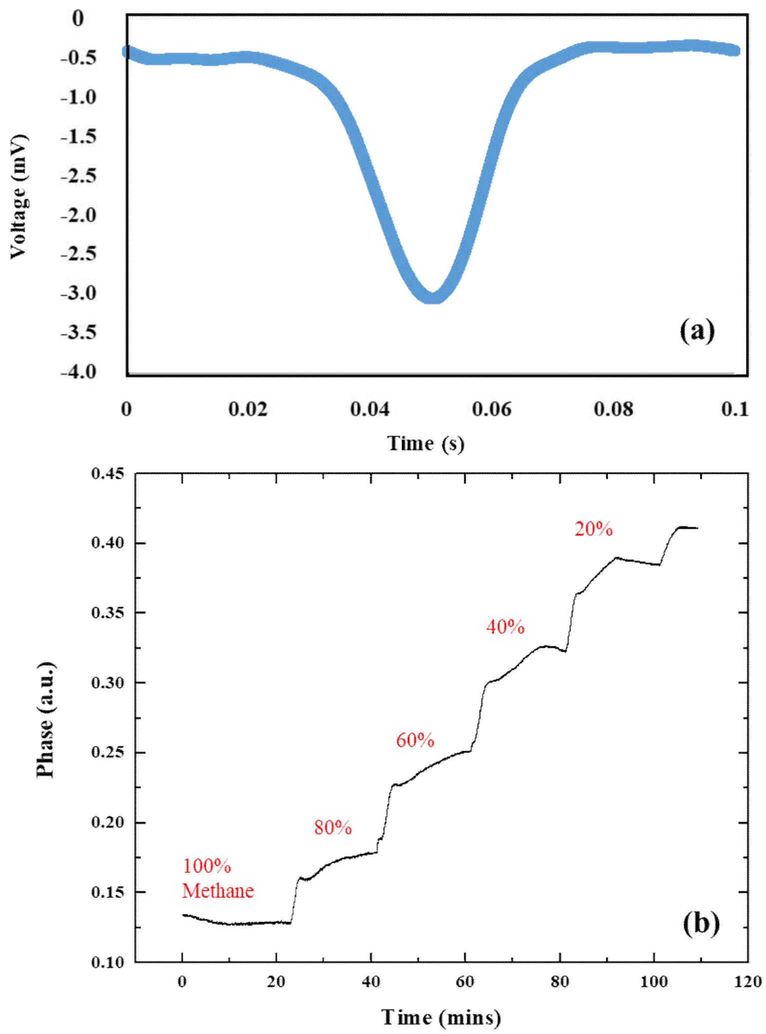

Figure 4. (a) Phase signal from phase CLaDS in 0.1 second ramp scanning period. (b) Methane measurement in high concentration circumstances.

The phase response of a single ramp period covers one absorption line of methane. Different concentration brings about different phase changes. The linear relation between methane concentration and phase changes has been proved in high absorbance conditions. Comparing with exponential relation of Beer-Lambert law, phase CLaDS has a much higher maximum limit. The low concertation measurement has been restricted due to the noise of circuits' imbalance and asymmetry. The performance of system is far from optimal that can be improved by choosing narrow linewidth laser diode and redesigning passive analog circuits.

5. CONCLUSION

In this paper, the phase CLaDS has been put forward to DSB-SC with passive demodulation scheme. The methane as gas sample has been measured under several high concentration circumstances. Laser light with wavelength 1665.9 nm scanned the $2\nu_3$ band of methane and carried the concentration information by passing through gas cell. Two sidebands of DSB-SC generated the beating signals which can be extracted by passive demodulation with RF mixer and RF multiplier. The phase of beating signal depending on gas concentration has been constructed mathematically. And it also has been verified by experimental results. Different from WMS, the phase CLaDS offers linear relation in concentration measurement. And the passive demodulation pushes the system's requirement to the lowest level.

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