Application of Sinusoidal Phase Modulation Technique for Infrared Spectrum Measurement by Fourier Transform Method

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Abstract

The Fourier Transform Infrared (FTIR) spectrometer is widely utilized for the detection and identification of gas in laboratories and open environments. The measurement sensitivity and range of the spectrometry are limited due to the strength of the absorption or emission signals. This study proposes the use of the sinusoidal phase modulation technique to improve the signal to noise ratio (SNR) of the detected signal of an FTIR spectrometer. In this technique, a sinusoidal signal is applied to a voice coil to create movement of a mirror. Hence, the intensity of the interference signal is a series of harmonics. A synchronous detection (lock-in amplifier) is then utilized to detect and amplify only one suitable harmonic and removed all other harmonics and noise. Therefore, the SNR of the harmonic is improved significantly. In this paper, a weak infrared emission from a commercial heat-lamp is detected successfully using the proposed system.

Keyword: FT-TR spectroscopy, Frequency modulation, Phase modulation, Michelson interferometer.

1. Introduction

Fourier Transform Infrared (FT-IR) spectrometers are powerful instruments for measurements of the intensity of infrared radiation as a function of frequency or wavelength [1, 2]. The instruments are based on the idea of the interference of radiation between two beams to generate an interferogram. The intensity of the interference signal is a function of the optical path difference (OPD) change between two beams. When Fourier Transform algorithm on the signal is performed, the frequency (wavelength) respond can be determined. Different FT-IR spectrometers used different interferometers, such as Michelson interferometer [3], Fabry-Perot interferometer [4], and grating interferometer [5]. Among these kinds of the spectrometer, the FT-IR spectrometers using the Michelson interferometers are preferred. These have some advantageous features over other techniques such as high precision and high energy throughout. In this paper, the characteristics of the FT-IR spectrometer based on the Michelson interferometer is first investigated.

Actually, the influence of environmental background limits the measurement precision of the FT-IR spectrometer. To remove the background effects, some modulation methods were employed. The earliest spectrometer used a chopper to modulate the intensity of the radiation sources [6]. The background noise can be eliminated using mechanical choppers and the synchronous detection (lock-in amplifier technique). The main disadvantage of this method is that the beam of radiation is interrupted by the chopper, the reduction in output is significant. Wavelength/frequency modulation technique has the advantages over the amplitude modulation method [7]. Both the reduction in output and the background noise are minimal [8]. However, this technique requires a high-cost electro-optic modulator (EOM) and it still has some residual amplitude modulation.

In this paper, a simple phase modulation method to improve the signal to noise ratio of an FTIR spectrometer is proposed. In the proposed system, the OPD between two arms of the Michelson interferometer is modulated by modulating the oscillating of the mirror. Hence, the intensity of the interference signal is series of harmonics and each harmonic is a function of the OPD. Using the lock-in amplifier technique [9], any harmonic of the interference signal can be detected accurately without noise effect. The frequency/wavelength respond is then determined using Fourier Transform method. In the experiment, our proposed system is utilized to detect an infrared radiation from a commercial heat-lamp.

2. Measurement principle

2.1 Phase modulation Michelson interferometer

The schematic diagram of the FT-IR spectrometer based on the Michelson interferometer is shown in figure 1. The radiation from an IR source that is placed at the focal point of a parabolic mirror (PM1) propagates to a beam splitter (BS). The beam

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splitter is made of a special material that transmits half of the radiation striking it and reflects the other half. One beam passes through the beam splitter to a fixed mirror and the second reflects off the beam splitter to a moving mirror. The moving mirror is driven by a voice coil actuator and it can move back and forth precisely around a balanced point. The fixed and movable mirrors reflect the radiation back to the beam splitter. Another parabolic mirror (PM2) directs the combined beam into an IR detector. Concurrently, a He-Ne laser propagates the same path with the IR radiation. The displacement of the moving mirror is determined accurately using the interference signal of He-Ne laser that is collected using a photo-detector. The infrared spectrum is obtained by first collecting an interferogram using the interferometer, and then performing a Fourier Transform on the interferogram to obtain the spectrum.

In this section, we propose a new method to improve SNR of an FT-IR spectrometer using the ph-

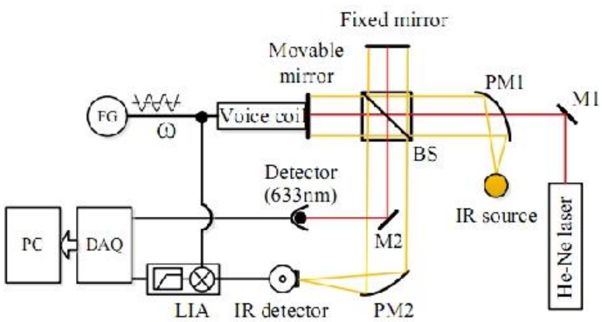

Fig. 1. Schematic diagram of FT-IR spectrometer. PM: Parabolic mirror; M: Mirror; BS: beam splitter; FG: function generator; LIA: lock-in amplifier; DAQ: data acquisition; PC: personal computer.

-ase modulation technique. When the moving mirror is modulated at a modulation frequency ω_m so that the delay time τ between two arms of the Michelson interferometer (τ =OPD/c; c is the speed of light) varies with time as the following equation [10]

$$\tau(t) = \tau_0 + \Delta\tau sin\omega_m t. \quad (1)$$

where τ_0 is the initial delay time caused by the unbalanced length between two arms and $\Delta\tau$ is the modulation excursion.

For a monochromatic radiation of frequency, the intensity of the interference signal is given as

$$I(\tau,t) = I_0\{1 + cos2\pi\upsilon(\tau_0 + \Delta\tau sin\omega_m t)\}, \quad (2)$$

where I_0 is the average intensity. Using the Bessel function, Eq. (2) is given by

$$I(\tau,t) = I_0\{1 + \cos(2\pi\upsilon\tau_0)[J_0(2\pi\upsilon\Delta\tau) + 2\sum_{k=1}^{\infty}(J_{2k}(2\pi\upsilon\Delta\tau)\cos 2k\omega_m t)] - \sin(2\pi\upsilon\tau_0)2\sum_{k=1}^{\infty}(J_{2k-1}(2\pi\upsilon\Delta\tau)\sin(2k-1)\omega_m t)\}. \quad (3)$$

Equation (3) shows that the interference signal of the modulated interferometer is a series of harmonics. Therefore, any harmonic from the signal can be detected using the lock-in amplifier technique [8, 9]. When the signal enters a lock-in amplifier, it is first multiplied by a reference value at a chosen frequency and then passes through a low-pass filter (LPF). Therefore, the amplitude of any harmonic at a significant modulation frequency can be accurately detected and all other higher order harmonics are removed. Hence, we can detect a pure harmonic without noise. This signal is then amplified with a suitable factor using an amplifier that is integrated into the lock-in amplifier. In this study, the first harmonic is utilized. Using the lock-in amplifier, the intensity of the first harmonic is

$$I_1 = 2I_0 J_1(2\pi\upsilon\Delta\tau)\sin 2\pi\upsilon\tau_0. \quad (4)$$

When a polychromatic radiation source enters the Michelson interferometer, but has a spectral distribution given by I(υ) as shown in Eq. (2), and the light at different frequency υ is incoherent, then the total intensity can be found be adding intensities for different υ

$$I(\tau,t) = \int_0^{\infty} I(\upsilon)\{1 + cos2\pi\upsilon(\tau_0 + \Delta\tau sin\omega_m t)\}d\upsilon. \quad (5)$$

In the same way, as a monochromatic is used, using the lock-in amplifier technique, we can determine the total intensity of the first harmonic at different frequency υ

$$I_1(\tau,t) = \int_0^{\infty} I_1(\upsilon)\, 2I_0 J_1(2\pi\upsilon\Delta\tau)\sin 2\pi\upsilon\tau_0\, d\upsilon. \quad (6)$$

The right-hand side is nothing more than the sine form of the Fourier transform of $I_1(\upsilon)$ so we have succeeded in writing an explicit form of the relation $I_1(\tau,t)$) = F{$I_1(\upsilon)$}. When the Fourier Transform algorithm is performed, both the amplitude and frequency of all components of the radiation spectrum are determined.

2.2 Determination of radiation frequency of based on the zero path difference point

The zero path difference point (ZPD) is located where the moving and fixed mirrors are the same distance from the beam splitter. Therefore, all components of radiation with different frequencies are in-phase at the ZPD. Their contributions are all at maximum and a very strong signal is produced by the IR-detector. When the OPD increases, different frequencies produce interference peaks at different positions of the movable mirror.

The laser He-Ne is utilized to measure the displacement of the moving mirror from the ZPD. The laser beam propagates the same path as the IR-radiation in the interferometer and produces its own interferogram at a photo-detector. This signal is used as an extremely accurate measure of the OPD. Therefore, when the moving mirror moves away from the ZPD, the position of any peak in the interferogram caused by different frequencies of the IR- radiation is determined. A noteworthy is that, at any peak position of the interferogram from the ZPD, the displacement of the moving mirror is the wavelength of the radiation.

3. Experiments

The experimental system is shown in figure 2. A commercial heat-lamp was used as an IR source. The spectrum of the lamp was first measured using a commercial radiometer (12-550 Mark III radiometer, Infrared Systems Development Corp.) and used as a reference. A modulation frequency of 20 Hz was supplied for the voice coil actuator to modulate the OPD, hence the delay time between two arms of the interferometer was modulated. A lock-in amplifier (PS1 Sciencetech Inc.) was used to detect the first harmonic from the interference signal. The cutoff frequency of the lock-in amplifier was 1Hz. The interference signal of radiation is collected using an IR-detector (MCT-14-10-LN, Sciencetech Inc.) that was cooled using Nitrogen liquid.

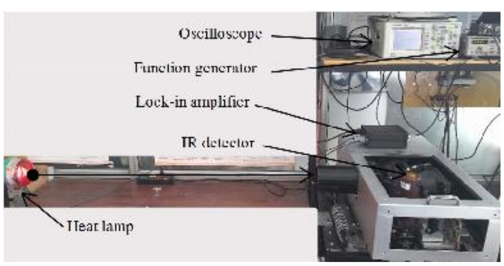

Fig. 2. Experimental system.

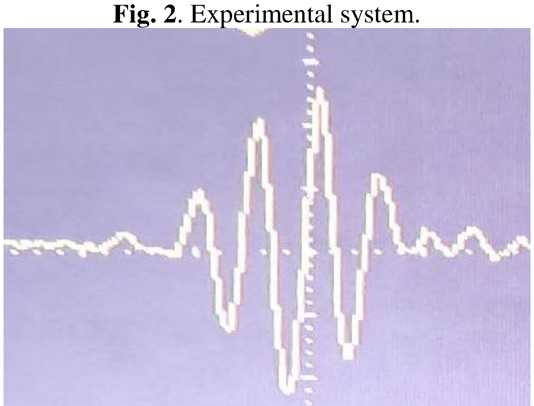

Fig. 3. Interferogram of the heat-lamp source

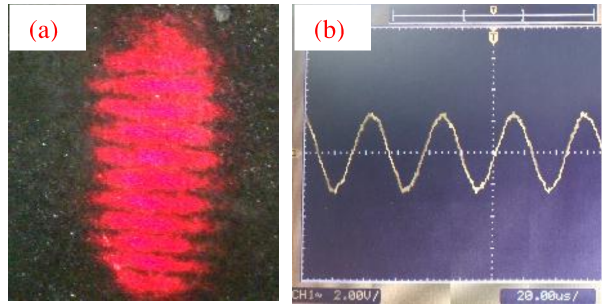

Fig. 4. He-Ne laser interference signal. (a): interference fringes; (b): intensity of the interference signal.

The ZPD point can be detected by monitoring the interference signal when all different frequencies of radiation were in phase and they made a very strong signal as shown in figure 3. The ZPD point was the biggest spike in the center of the burst. The interference signal of He-Ne laser is shown in figure 4. This signal was used to determine the displacement of the movable mirror from the ZPD

The spectrum of the heat lamp measured using our proposed system is shown in figure 5(a). Concurrently, the spectrum of the lamp was measured using the commercial radiometer (12-550 Mark III radiometer, Infrared Systems Development Corp.), figure 5(b). The measurement range of the radiometer covers the 1 to 16 um range. The experiment results using our proposed system and using the commercial radiometer show the same spectrum. The strongest radiation was figured out at the wavelength of 3,2 μm. It means that the spectrum of the heat lamp was successfully determined using our proposed system.

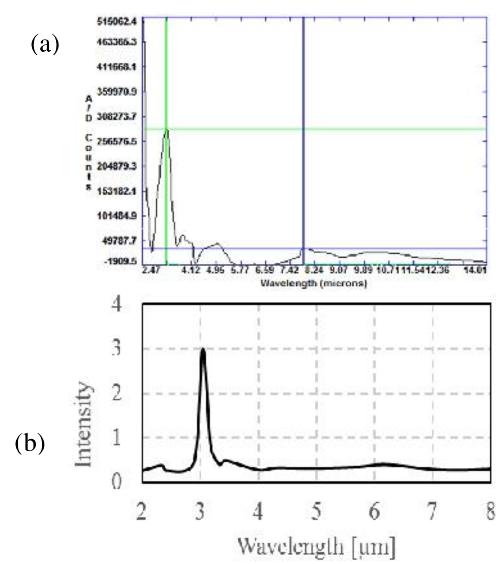

Fig. 5. IR spectrum of the heat lamp, (a) the spectrum obtained using the radiometer, (b) the spectrum obtained using our system (cutoff frequency of 1Hz).

4. Conclusion

The sinusoidal phase modulation FT-IR spectrometer was performed. The advantageous features of the sinusoidal phase interferometer and the lock-in amplifier detection were analysed. The first harmonic of the modulated interference signal was used for the spectrum measurement of broadband radiation. The spectrum of a commercial heat-lamp was determined using our proposed method. This result opened a direction to develope FT-IR spectrometer for a broadband radiation source such as a blackbody or IR-lamps.

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