REVIEW OF SCIENTIFIC INSTRUMENTS 88, 106104 (2017)

Note: Demodulation of spectral signal modulated by optical chopper with unstable modulation frequency

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(Received 16 August 2017; accepted 20 September 2017; published online 6 October 2017)

When an optical chopper is used to modulate the light source, the rotating speed of the wheel may vary with time and subsequently cause jitter of the modulation frequency. The amplitude calculated from the modulated signal would be distorted when the frequency fluctuations occur. To precisely calculate the amplitude of the modulated light flux, we proposed a method to estimate the range of the frequency fluctuation in the measurement of the spectrum and then extract the amplitude based on the sum of power of the signal in the selected frequency range. Experiments were designed to test the feasibility of the proposed method and the results showed lower root means square error than the conventional way. *Published by AIP Publishing.* https://doi.org/10.1063/1.5000416

An optical chopper is a commonly used device in optical systems to modulate or to attenuate the light flux.[1–4] Its rotating chopper wheel will periodically block the light to generate a modulated optical signal. The modulation can shift the unchanged or slowly varying signal to the modulation frequency.[5] In the demodulation process, only the component at the modulation frequency is obtained, which can suppress the influence of the 1/f noise, the direct current offset, and the evenly distributed random noise. In other words, it can improve the signal-to-noise ratio (SNR) in the spectral measurement. Two ways are widely used for demodulation of the signal: by performing digital lock-in algorithm and through Fourier transform (FT).[6,7] However, due to the mechanical error of the wheel and the unstable rotation speed, it is inevitable that the fluctuation of the modulation frequency occurs. The mismatch of frequency for calculating the signal amplitude and the actual signal frequency will have impact on the measurement precision.[5,6] To effectively extract the signal with unstable modulation frequency, we proposed a method to estimate the range of the frequency fluctuation in the spectral measurement and extract the signal based on the estimated frequency range.

The modulation functions of the light flux are determined by the design of the chopper wheel and the profile of the light beam.[2] In this paper, the modulated signals are approximately regarded as a square wave signal. The Fourier series of a square wave can be expressed as Eq. (1), where A and f are the amplitude and the modulation frequency, respectively,

$$s(t) = \frac{A}{2} + \frac{2A}{\pi}\left(\sin(2\pi ft) + \frac{1}{3}\sin(2\pi 3ft) + \frac{1}{5}\sin(2\pi 5ft) + \cdots\right) + \text{noise}. \quad (1)$$

According to Eq. (1), by applying the FT to the acquired signal sequence, the amplitude of the modulated signal can be obtained from the amplitude of the base-frequency component. However, because the optical chopper is controlled by an electric motor, there is jitter in its rotating speed, which causes unstable modulation frequency of the light flux. An example is given here to show the influence of the frequency fluctuation on the signal in the frequency domain. We generated a square wave signal sequence of 8000 points when the signal frequency varies from 9.6 Hz to 10.4 Hz with sampling frequency 100 SPS.

The result of the FT is illustrated in Fig. 1. It can be seen that there is no sharp peak at frequency 10 Hz and there are several frequency components around 10 Hz. The amplitude around 10 Hz is about 0.1-0.2 in Fig. 1, while the number is about 0.6366 ($2/\pi$) in theory according to Eq. (1). The result shows that when the frequency fluctuation occurs, the result may be severely distorted through the FT method.

To precisely obtain the amplitude of the signal with unstable modulation frequency, it is needed to utilize all the Fourier components in the fluctuation frequency range. When the frequency of the chopper is set to f_0, its actual frequency can be any value in the range of $[f_0 - \Delta f, f_0 + \Delta f]$ due to the frequency jitter in the chopper. The modulation will generate several Fourier components with the frequency $[f_0 - \Delta f, f_0 + \Delta f]$. The amplitude of the original signal cannot be precisely obtained based on only one frequency component. Assuming the measured signal sequence is $s[n]$, its Fourier transformed value can be represented by the following equation:

$$F(k) = FT(s[n]). \quad (2)$$

Assuming the amplitude of the measured signal is A, the average power of the fundamental frequency component is $4A^2/\pi^2$. When the frequency of the square wave changes with the frequency range $[f_0 - \Delta f, f_0 + \Delta f]$, the total power in the

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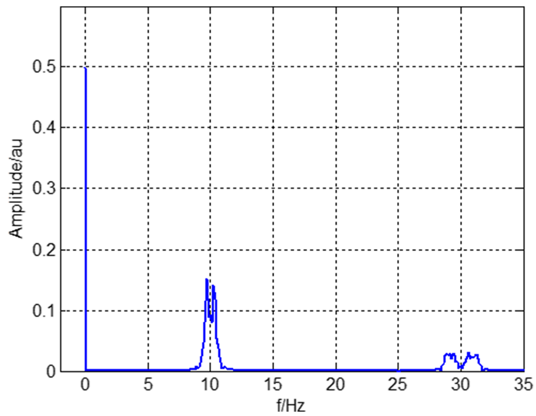

FIG. 1. Frequency-amplitude plot of a square wave with unstable frequency from 9.6 Hz to 10.4 Hz.

frequency range $[f_0 - \Delta f, f_0 + \Delta f]$ is still $4A^2/\pi^2$, as is shown in Eq. (3). In Eq. (3), $n1$ and $n2$ are corresponding to frequency $f_0 - \Delta f$ and $f_0 + \Delta f$, respectively,

$$P = \sum_{n1}^{n2} |F(k)|^2 = 4A^2/\pi^2. \tag{3}$$

The amplitude of the measured signal can be obtained using the following equation:

$$A = \frac{\pi}{2}\sqrt{\sum_{n1}^{n2} |F(k)|^2}. \tag{4}$$

However, as the jitter of the chopper frequency is random, the maximum and minimum frequencies during the measurement time cannot be precisely obtained. We may select a frequency range that is larger than the possible frequency fluctuation for calculating the amplitude, but more noise may be introduced in the calculated results. Therefore, it is necessary to estimate them according to the fluctuation frequency range of the measured signal.

In spectral measurement, the spectrometer measures the intensity of light at each wavelength simultaneously. When the chopper modulates the spectrum signal, the phases of useful signals at each wavelength are the same, whereas the phases of noises are randomly distributed. When the signal is modulated by the chopper with a frequency range of $[f_0 - \Delta f, f_0 + \Delta f]$, the phases of Fourier components in this range should be approximately the same at each wavelength. The value of $F(k)/|F(k)|$ should be at the adjacent position of a unit circle at each frequency when the value of k is in the frequency fluctuation range. When the value of k is out of the modulation frequency range, the value of $F(k)/|F(k)|$ differs greatly at different wavelength. The steps for estimating the frequency fluctuation range are as follows:

1. Apply the Fourier transform to the spectrum signal sequence according to the wavelength sequence, where $F_\lambda(k)$ represents the value of the frequency component of k at wavelength of λ, and then calculate the value of $F_\lambda(k) / |F_\lambda(k)|$. For the convenience of description, we set $M_\lambda(k) = F_\lambda(k) / |F_\lambda(k)|$.
2. Use the equation $\sigma(k) = \sqrt{\sum_{i=1}^{n} (M_{\lambda i}(k) - \overline{M(k)})^2 / n}$ to calculate the degree of dispersion of $M_\lambda(k)$ at the frequency k, where λi represents the ith wavelength.

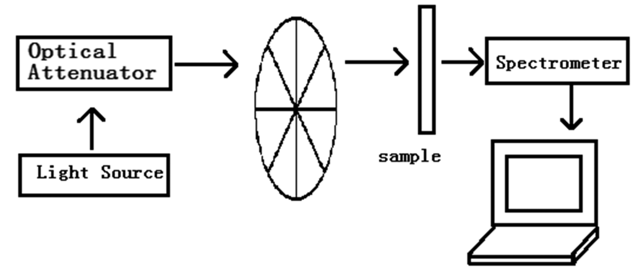

FIG. 2. Experiment setup of spectral measurement with the optical chopper.

3. Set the threshold value σ_0, find a minimum number of $n1$ that meet the requirement $\sigma(n1) < \sigma_0$ near the fundamental frequency and a maximum number of n2 that meet the requirement $\sigma(n2) < \sigma_0$. The range [n1, n2] is the estimated frequency fluctuation range.

We conducted experiments to test the feasibility of the proposed method. Figure 2 is the illustration of the experimental setup. It is composed of a light source, an optical attenuator, an optical chopper, a grating spectrometer, and a personal computer. The light source is a SuperK compact light source manufactured by NKT Photonics with a spectrum range of 300–2400 nm and an average output power of 100 mW. The grating spectrometer is AvaSpec-HS1024*58TEC-USB2 manufactured by Avantes, with a spectrum resolution of 1.5–2.0 nm and a spectrum wavelength range of 299.87–1160 nm. The optical chopper is a Model SR540 CHOPPER manufactured by Stanford Research System, Inc.

The amplitudes of the signals were extracted first by using the traditional FT method. We also estimated the frequency fluctuation range in each measurement using the method proposed in this paper and then calculated the amplitude according to Eq. (4). The results obtained from both methods were calibrated by measuring known optical signals. During the experiment, the integral time of the spectrometer was set to 10 ms, which means the sampling rate is 100 SPS. The frequency of the chopper was set to 10 Hz. 100 measurements were conducted with each measurement last for 5 s. The setting of the threshold σ_0 is not easy to be done. It should be adjusted according to the performance of the spectrometer, the stability of the light source, and other aspects. If the

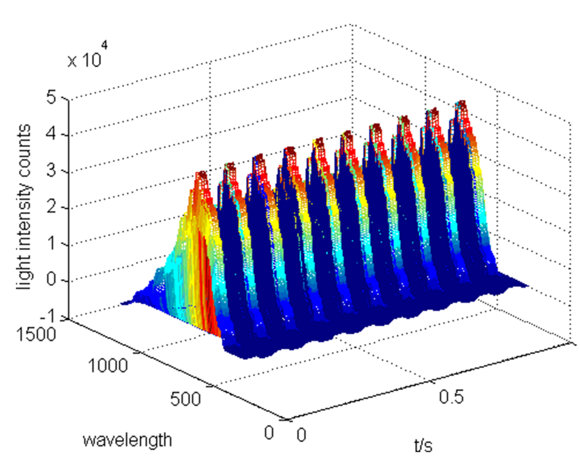

FIG. 3. A 3-dimension display of the measured spectra.

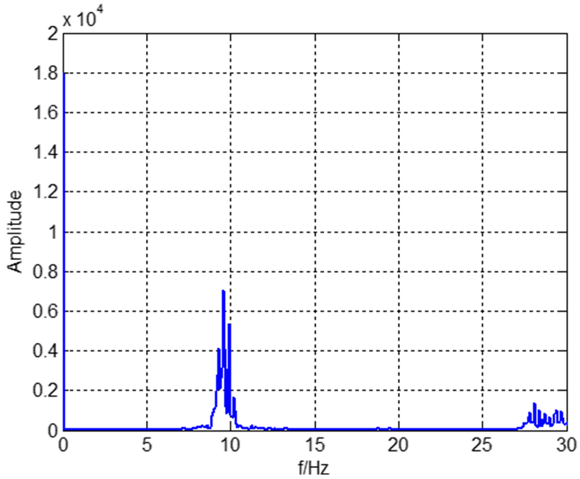

FIG. 4. A frequency-amplitude diagram of the optical signal measured at a wavelength of 600 nm.

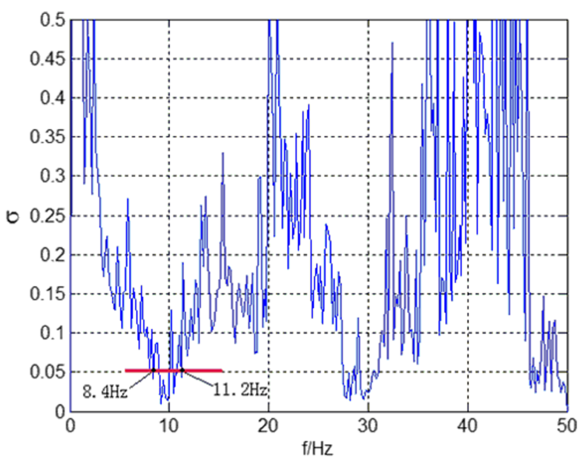

FIG. 5. σ-*f* curve of one of the measurements.

threshold σ_0 is larger than necessary, the estimated frequency range would be broader than the actual frequency fluctuation range. If the threshold σ_0 is small, the estimated frequency range would be narrower than the actual frequency fluctuation range. It is suggested to apply different σ_0 to a relatively long period of signal data with a standard sample to find the best one in advance. In this study, the threshold value σ_0 was set to 0.05.

Figure 3 displays one of the original modulated spectral signals. In Fig. 4, the frequency-amplitude diagram of an optical signal measured at wavelength 600 nm. It appears that there are several Fourier components around 10 Hz, which show that there is fluctuation in the chopper frequency. To show how to estimate the frequency fluctuation using σ and σ_0, a diagram of σ-*f* of one of the measurements is displayed in Fig. 5. It shows that σ tends to decrease when the frequency is closed to the modulation frequency or its odd harmonics. The threshold σ_0 is set to 0.05. The minimum and maximum frequencies that meet the requirement $\sigma(f) < \sigma_0$ near the modulation frequency are 8.4 Hz and 11.2 Hz, as is shown in Fig. 5.

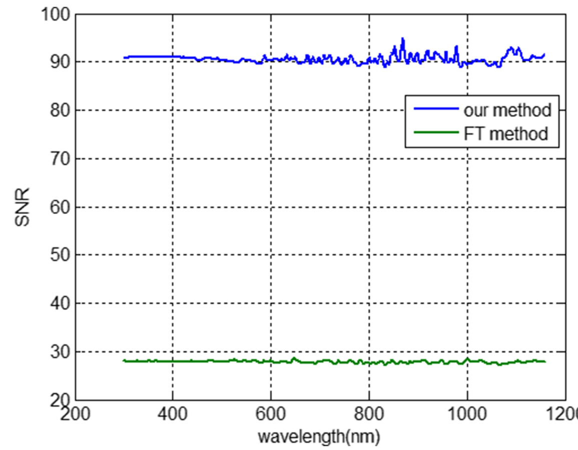

FIG. 6. SNR of the spectrum with two different methods.

We defined the signal to noise ratio (SNR) as the ratio of the mean value of 100 measurements and the standard deviation. Since it was not possible to obtain the real value of the intensity, the SNR was used to evaluate the performance of the demodulation methods in this study. Figure 6 shows the SNR of obtained spectral signals with two different methods. The SNR of the spectral signal demodulated using the method in this paper is about three times higher than that using the FT method.

In optical signal detection by optical chopper modulation, the signal-to-noise ratio of spectrum signals extracted by the digital lock-phase technique or Fourier transform is comparatively low due to the fluctuation of chopper frequency. This paper proposed a method of superimposing many frequency components within the chopper fluctuation frequency range and extracting the spectrum signals. The phases of useful signals are the same, theoretically, at different wavelengths of the modulated signal. The dispersion of the phases of the Fourier transformed components at each wavelength was utilized to estimate the jitter frequency range of the chopper. The experiment compared two methods for extracting the amplitude of modulated signals, and the experimental results showed that the proposed new method can effectively extract the signal amplitude with a higher signal-to-noise ratio.

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