Detection of weak Modulation signal by Digital Phase-locked Amplifier

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Abstract: In the signal detection of two-dimensional material light modulation spectrum, the modulation signal is very weak and often submerged in the noise, so it is difficult to detect the modulation signal in the research. In order to detect weak modulation signals, according to the principle of digital phase lock amplification, this paper realizes the orthogonal digital phase lock method in MATLAB, and studies the extraction of modulation signals in the optical modulation spectrum. The results show that when the average noise is 20 μV, the digital phase-locked amplifier can effectively extract the modulation signal of 1 μV. When the amplitude, phase and type of modulation signal change, the extraction of modulation signal will not be affected.

1. Introduction

Two-dimensional material refers to the material in which electrons move freely on only two dimensions of non-nanometer scale [1]. In the study of energy band structure of two-dimensional materials, optical modulation spectrum is one of the very important research methods [2]. Because the laser with frequency modulates the band structure of the material, the reflected light contains the information of laser modulation. The reflected light intensity is defined as R, and the reflected light is slightly changed by the influence of the modulation signal, which is defined as the modulation signal ΔR [3]. The noise caused by the system is usually white noise, defined as Noise. So the signal detected by the sensor is R+ΔR+Noise. According to the principle of light modulation spectrum and two-dimensional material properties, their signal characteristics are shown in Figure 1. The size of R usually ranges from 0.1V to 1V, and it varies slowly over time. ΔR is usually a few μV or so. Noise is about a few μV or bigger. As shown in figure 1 (d), R is usually completely drowned in noise. Therefore, how to effectively get ΔR is two-dimensional material one of the direction of the light modulation spectroscopy.
In this paper, the digital phase-locked technology is studied to extract the modulation signal $\Delta R$ from the optical modulation spectrum of two-dimensional materials. By using digital orthogonal phase-locked amplifier, the extraction process of amplitude and phase information of modulation signal by digital phase-locked amplifier is studied when the waveform, amplitude and phase of the modulated signal are changed.

2. Digital phase lock principle and simulation process

Phase-locked amplifier is a kind of equipment which uses correlation detection principle to detect weak signal [4]. It has strong weak signal detection ability and strong anti-interference ability. Therefore, it has a wide range of application prospects in the field of weak signal detection, and it is one of the effective tools to study the optical modulation spectrum of two-dimensional materials. Phase-locked amplifier is based on phase-locked amplification technology [5].

The basic principle of phase-locked amplification technology is shown in Figure 2. It is mainly composed of three parts: signal channel, reference signal channel and correlator [6]. The signal channel is mainly composed of a high-pass filter. The output signal of the detector is filtered by high-pass filter to get the mixed input signal ($f_i$) of modulated signal and noise to be tested. The reference signal channel generates a signal with the same frequency as the modulation signal according to the modulation frequency. The correlator is mainly composed of phase sensitive detector (PSD) and low pass filter (LPF).

Assuming that the laser frequency is $f$ and the laser modulation is sinusoidal modulation, then the angular frequency $\omega_0$ is $2\pi f$. The noise source of the signal is mainly Gaussian white noise (Noise). Input signal $f_i$ is represented as:
\[ f_i = A \sin(\omega_0 t + \theta) + \text{Noise} \tag{1} \]

Where, \( A \) is the signal amplitude and \( \theta \) is the initial phase of the signal. Here, amplitude \( A \) and phase \( \theta \) are measured.

If the amplitude of the reference signal is \( B \), the reference signal is set to be:

\[ f_{\text{ref}} = B \sin(w_0 t) \tag{2} \]

Then the multiplier output is:

\[ f_c = f_i * f_{\text{ref}} = \left( A \sin(w_0 t + \theta) + \text{Noise} \right) B \sin(w_0 t) \]

\[ = \frac{1}{2} A B \cos(\theta) \frac{1}{2} A B \cos(2 \omega_0 t + \theta) + \text{Noise} B \sin(w_0 t) \tag{3} \]

From formula (3), it can be seen that after the signal passes through the low-pass filter, the double frequency component and the double frequency component are filtered out, and what is left is:

\[ f_{\text{out}} = \frac{1}{2} A B \cos(\theta) \tag{4} \]

The signal contains the amplitude \( A \) and the phase \( \theta \) of the signal \( \Delta R \), but \( A \) and \( B \) cannot be obtained separately. In order to obtain accurate amplitude and phase information, the invention is realized by an orthogonal double-phase locking technology. The principle of the orthogonal double phase locking technique is shown in Figure 3. The nature of the dual phase-locked amplifier is to add a reference channel on the basis of a common phase-locked amplifier. The signal frequency and the amplitude of the two reference channels are consistent, and the initial phase difference is \( \pi/2 \). The technology can accurately obtain the amplitude and phase information of the measured signal and is not affected by the phase shift.

![Figure 3. Schematic diagram of orthogonal two-phase locking technology](image)

From the above analysis, it can be seen that for the reference channel 1, after the input signal and the reference signal 1 are multiplied and filtered by the correlator, the following can be obtained:

\[ f_{\text{out1}} = \frac{1}{2} A B \cos(\theta) \tag{5} \]

For reference channel 2, the signal and the reference signal 2 are multiplied and filtered by the correlator, there are:

\[ f_{\text{out2}} = \frac{1}{2} A B \sin(\theta) \tag{6} \]

The following can be obtained:

\[ \theta = \arctan\left( \frac{f_{\text{out2}}}{f_{\text{out1}}} \right) \tag{7} \]

The amplitude is:

\[ A = 2 \sqrt{f_{\text{out1}}^2 + f_{\text{out2}}^2} / B \tag{8} \]

According to the principle of orthogonal phase-locked technology, the simulation process of
orthogonal digital phase-locked amplifier is realized in MATLAB environment. In the simulation model, the Butterworth low-pass filter is used [7-8]. The modulated signal is a sinusoidal signal with a frequency of 80Hz, phase of 60° and amplitude of 5μV. The frequency of reference signal 1 and 2 is 80Hz, the amplitude is set to 1V, and the phase is 0° and 90° respectively. The noise is set as gaussian white noise.

3. Experimental results and analysis

![Graph](image)

Figure 4. Signal phase and amplitude obtained by orthogonal digital phase-locked amplifier
(a) Detected phase; (b) Amplitude detected

Figure 4 is an orthogonal digital phase-locked amplifier to obtain the phase and amplitude of the modulation signal. As can be seen from the figure, the output of the phase-locked amplifier is stable after about 0.5s, when the phase is 59.64 °and the amplitude is 5.085 μV. Compared with the phase and amplitude of the input modulation signal, the errors are 0.6% and 1.7%, respectively. Considering the influence of noise and system error, the result is very ideal.

![Graph](image)

Figure 5 Changing modulation signal amplitude, phase and amplitude of signal obtained by phase-locked amplifier. (a) Phase output results; (b) Amplitude output results; (c) The relationship between amplitude output and modulation signal amplitude

Figure 5 is the simulation output of a digital phase-locked amplifier when the modulation signal with the same initial phase and different amplitude is input. The phase of the modulation signal is 60°, and their amplitudes are 1 μV, 2 μV, 3 μV and 4 μV, respectively. It can be seen from Figure 5(a) that their phase output is stable at 60° after 0.5s, and the maximum deviation between the output phase and the input phase of the modulation signal is 0.27°. It can be seen from Figure 5(b) that although the...
input amplitude of the modulation signal is different, after 0.5 s, the output of the digital orthogonal phase-locked amplifier is stable at 1 μV, 2 μV, 3 μV, 4 μV, and the maximum deviation is 0.004 μV. The deviation is very small. Figure 5(c) shows the relationship between the stable output of amplitude and the input amplitude of modulation signal. The stable output result of amplitude is equal to the amplitude of modulation signal input, and the error offset is 0.1%. Considering the influence of system error, the output result is also very ideal.

Figure 6. Modulating signal phase, phase and amplitude of signal obtained by digital phase-locked amplifier. (a) Phase output results; (b) amplitude output results; (c) the relationship between the phase output results and the phase change of the modulated signal

Figure 6 is the simulation output of a digital phase-locked amplifier with the same amplitude and different initial phase of the modulation signal. The amplitudes of the modulation signals are 5 μV, and their phases are 60°, 45°, 36° and 30°, respectively. It can be seen from Figure 6(a) that although the initial phase of modulation signal is different, after 0.2 s, the output of the digital orthogonal phase-locked amplifier is stable at 60°, 45°, 36° and 30°, respectively. They have a maximum deviation of 0.6° from the modulated signal input phase. Figure 6(b) shows the signal becomes stable after 0.4s. The output results of the amplitudes are stable at 5 μV, and the maximum deviation between these output amplitudes and the input amplitudes of the modulation signal is 0.012 μV. Figure 6(c) shows the relationship between the output result of the phase and the input phase of the modulation signal. It can be seen that the phase output result of the orthogonal phase-locked amplifier is equal to the phase of the signal input after the stability, and the error offset rate is only 1%, which meets the requirements of the design.

Figure 7. Output results of orthogonal phase-locked amplifier (a) Different modulation signal types; (b) Amplitude output results

Figure 7 is the simulation output of orthogonal phase-locked amplifier for detecting different types
of modulation signals. When the noise is Gaussian white noise, the types of modulation signal are sinusoidal wave, square wave, triangular wave. Their amplitude and phase are 5 μV and 60 °, respectively. From Figure 7(a), the output of the orthogonal phase-locked amplifier begins to be stable after 0.5 s, and the output phase is stable at 60 °, in which the maximum output deviation of square wave phase is 1.6 °, and the deviation of sine wave and square wave phase output is very small, with a maximum deviation of 0.023°. From Figure 7(b), it can be seen that after 0.75s, the output of the ortho-locked amplifier to the amplitude is stable at 5 μV, and the maximum deviation of the stable output amplitude compared with the input amplitude is 0.051 μV. Considering the factors of system error, the orthogonal phase-locked amplifier is very ideal for the detection of modulation signal when the type of modulation signal changes.

4. Conclusion
In this paper, by analyzing the characteristics of optical modulation signal and combining with the amplification principle of digital phase-locked, the orthogonal digital phase-locked amplifier is simulated in MATLAB environment, and the extraction of modulation signal in optical modulation spectrum is studied by using the amplifier. The experimental data show that the digital orthogonal phase-locked amplifier can effectively detect the amplitude and phase of weak signal in background noise, and the detection is not affected by the type of weak signal, and the signal with high accuracy can be detected accurately, stably and accurately.

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