Windowed Fourier transform for surface plasmon resonance spectral interference signals

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Abstract: A novel signal processing method based on windowed Fourier transform (WFT) was presented in a phase detecting surface plasmon resonance (SPR) system using spectral interference. The principle of this phase retrieval algorithm was introduced detailedly. The main factors which can affect the precision was analyzed, such as the width of the window, sample frequency, threshold value etc. Calculations indicated that, it can achieve a desired detection limit only by picking up the appropriate parameters. From the achieved spectral phase difference, the detection limit we obtained is 3.894×10^{-7} RIU, while the theoretical value is 3.905×10^{-7} RIU, the precision of this algorithm is 0.28%. It is seen that the algorithm presents a higher precision. In addition, the algorithm is mathematically simple and it can be readily combined with commonly used data analysis methods.

Key words: WFT; surface plasmon resonance; analog optical signal processing; phase retrieval

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用于表面等离子体共振的加窗傅里叶变换法信号处理方法

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摘　要:提出了一种采用加窗傅里叶变换的新型信号处理方法,用于提取基于白光光谱干涉相位型表面等离子体共振系统中的相位信息。首先,详尽阐述了这种提取相位信息算法的基本原理;其次,分析了算法中影响精度的几项主要参数,如窗口宽度、采样频率、阈值等,分析表明,只有选取恰当的参数才能得到理想的探测精度;最后,根据实际算取的光谱相位差值得出实际探测精度为 3.894×10^{-7} RIU(折射率单位)。与之相对应的理论探测精度为 3.905×10^{-7} RIU。理论精度和实验精度误差为 0.28%。可以看出,这种算法具有很高的精度。另外,这种算法还具有简单、易与其他数值分析方法结合的优点。

关键词:加窗傅里叶变换; 表面等离子体共振; 模拟光学信号处理; 相位提取

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0 Introduction

Surface plasmon resonance (SPR) is an optical-electrical phenomenon caused by the interaction of incident light and the electron of thin mental lay. The SPR sensor instrument has the advantage of high-sensitivity, label-free analysis and less sample needed. With decades of research, it can be widely used in biometrics, chemistry and medicine applications. Compared with the traditional differential phase detecting SPR sensor based on laser detecting schemes, the white-light spectral interferometry presented much higher sensitivity and wider dynamic range of measurement[1-2]. The system using a broadband source combined with a Michelson interferometer has been widely used in SPR sensor system.

Many detection techniques have been developed with the purpose of getting useful information from SPR sensor systems. Usually, there are four parameters to measure the variation of refractive index, such as, intensity, angular, wavelength, and phase[1-2]. The phase modulation presents a higher sensitivity obviously[3]. In order to demodulate the phase information from the fringe intensity, there exist many suitable algorithms. For the spectrum recorded in the wavelength domain, the algorithms include two-point algorithm, Fourier transform algorithm, phase-locked loop method and the Kalman filtering method[4]. However, each method has their disadvantages, the computation is heavier and complicated, and it is difficult to achieve a high precision. In order to obtain a better result, it need to develop a simple and valid method.

In this paper, it adopted a new method of processing the interference signal extracted from SPR system is adopted, which is based on windowed Fourier transform (WFT) effectively applied in wavelength domain. It used the numerical simulations to perform the interference signals, and then it retrieved the phase information. It analyzed the main factors which are affecting the precision, such as the width of the window, sample frequency, threshold value etc. Calculations indicated that, it can achieve a desired detection limit with the appropriate parameters.

1 SPR sensor system and interference signals

Here it considered a new differential phase detecting SPR sensor system. The scheme adopted a white-light source for SPR excitation, with the fixed angle of incidence, the corresponding SPR phase change occurs at the optimized coupling wavelength[1,5].

The structure of SPR sensor system as shown in Fig.1, a warm-white light emitting diode (LED) through a broadband linear polarizer was directed by a collimator. The LED spectrum was divided into two paths by a broadband non-polarizing beam-splitter. In order to set up a Michelson spectral interferometer and compensate the excessive dispersion, it picked up two same Kretschmann prisms as the SPR sensor prisms. Other two mirrors were placed at the end, one of them aimed at adjusting the optical path difference in the air. The sensing chip was coated with a gold film. At the exit of the interferometer, a broadband polarizing beam splitter was divided the mixed interferogram into two polarizations. The collimators collected the optical signals, and the spectrometer detected them[6].

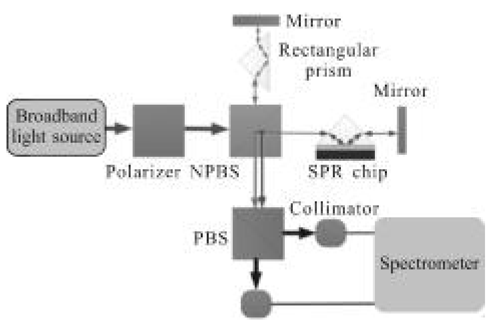

Fig.1 Scheme of phase detecting SPR sensor system

Based on published data for the prism-metal-dielectric sensing structure, we presented the numerical model based on up-mentioned system with BK7 glass as a Krestchmann prism coupler, the thickness of gold film is 50 nm, the incident angle is 69°, and pure water is contact with the gold film. The corresponding spectral interferograms is shown in Fig.2. The corresponding spectral differential phase between the p- and s-polarization is shown in Fig.3.

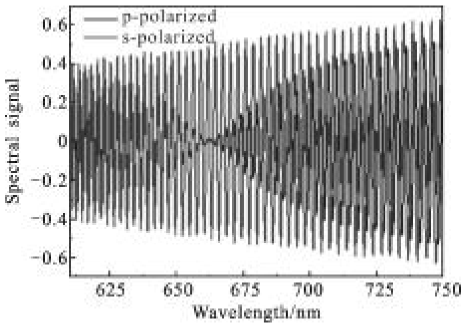

Fig.2 Spectral interferogram based on SPR sensor system

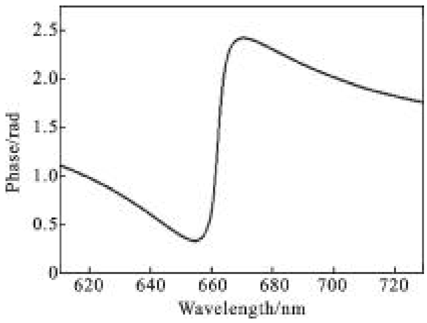

Fig.3 Spectral differential phase between p- and s-polarization

The theoretical resolution of its SPR sensor system can be estimated over a wide measurement range. The limit of detection (LOD) can be expressed as[1]:

$$\delta=\frac{\delta_n}{\delta_p}\sigma_n \tag{1}$$

Where δ is the LOD; δ_n is the refractive index change of the medium; δ_n is the phase shift which it need to calculate; and σ_n is the estimated phase noise. It take a small δ_n of 0.002 from 1.330 to 1.332 refractive index units (RIU), the spectral phase has shifted by about 51.21° at 662.00 nm, the phase measurement noise is 0.01, use the Eq.(1), the LOD is coming up to 3.905×10^{-7} RIU. This value of simulation presents a good sensitivity. Next step, it will introduce a new approach to calculate the phase shift from the spectral signals.

2 Principles of windowed Fourier transform

The WFT is a Fourier-related transform used to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time, is a special case of the short-time Fourier transform. In order to determine the phase distribution in white-light spectral interferometry, the output is always in the form of a fringe pattern as $f(\mathbf{x})$. It denoted $\mathbf{g}(\mathbf{x})$ is a window function, which can be chosen as a Gaussian function[7]:

$$\mathbf{g}(\mathbf{x})=\exp\left(-\frac{\mathbf{x}^2}{2\sigma^2}\right) \tag{2}$$

Where the parameter σ controls the spatial extension of $\mathbf{g}(\mathbf{x})$ means that it determined the width of the Gaussian window. Now, it need to denote $\mathbf{h}(\mathbf{u},\xi)=\mathbf{g}(\mathbf{u})\cdot\exp(j\xi\mathbf{u})$ then equations can be expressed as convolution. It use an approach based on a windowed Fourier filtering to transform the WFT spectral[8-10]. Finally, it can combine above equations together into a brief one:

$$\bar{f}(\mathbf{x})=\frac{1}{2\pi}\int_b^a[\overline{f(\mathbf{x})\otimes\mathbf{h}(\mathbf{x},\xi)}]\otimes\mathbf{h}(\mathbf{x},\xi)d\xi \tag{3}$$

Where $\overline{f(\mathbf{x})\otimes\mathbf{h}(\mathbf{x},\xi)}$ denotes a threshold value, which means the noise can be eliminated. After the fringe pattern is synthesized, the phase $\phi(\mathbf{x})$ which it want to obtain can be determined as:

$$\phi(\mathbf{x})=\mathrm{angle}[\bar{f}(\mathbf{x})] \tag{4}$$

In view of the above-mentioned equations, then, it can use the numerical simulation method to retrieve the phase information from the interfering signals.

3 Data processing with WFT

A modified algorithm was proposed, which is shown in a mathematical model, numerical simulations as well as in experiments that is effective for optical power correlated noise. Now, it have been using the WFT to calculate the phase information from respective p- and s-polarized spectral interferograms. Based on analyzing the main factors of precision, it picked up the appropriate parameters with the width is 0.28, sample frequency is 3 000, the threshold value is from 0 to 128, the gap is 0.4. It can see the transform signals as Fig.4, with the first multiplied by a Gaussian function, the spectral signals presents a periodical trend. Then, it extract the important phase information from the modified spectral signals with a series of commands. As same as the spectral signals, the differential phase it calculated was presenting a periodical trend. It can achieve followed outcome as see as Fig.5. And it choose a valid part of phase as Fig.6.

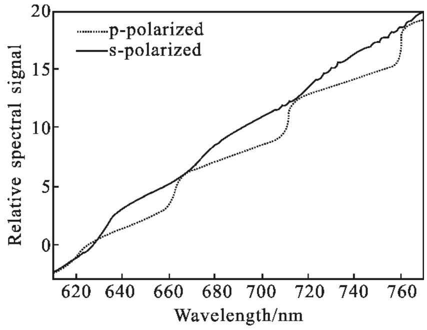

Fig.4 New spectral signals operated with WFT

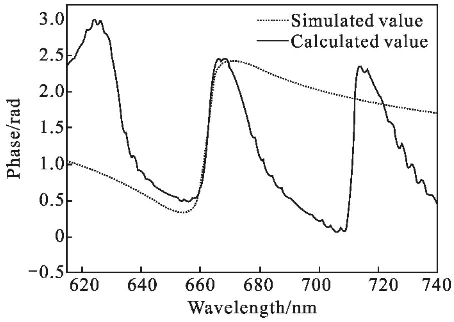

Fig.5 Calculated phase value and simulative value

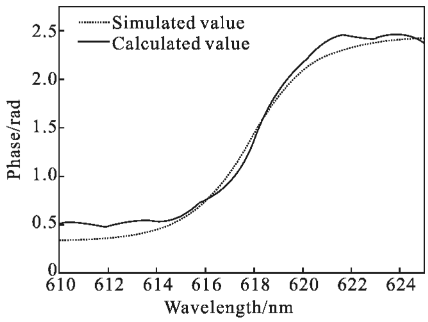

Fig.6 Valid part of phase

Use the same way it have mentioned above, it have found that the proposed technique has a detection limit as high as 3.894×10^{-7} RIU. Contrast with simulated result, it have calculated the precision of this algorithm as high as 0.28%. Next, it discuss the main factors how to affect the precision of the algorithm.

(a) The sample frequency affects the sample number of wavelength and signals directly. Only it control the sampling interval, it can choose the appropriate quantity of the parameters.

(b) The width of the window is the key factor which it had to pick up prudently. Consider the sample frequency of the signals, it need to ensure the width had covered the whole wavelength domain. At the same time, make certain that the width had separated the signal into suitable size so that it can observe the periodical trend. Then it can achieve a desired and concise differential phase. It choose a specific sample frequency and threshold value, then observe the subtle effect of phase value. As see as Fig.7, it choose the threshold value from 0 to 128, and in Fig.8 is from 0 to 133. Both of them adopt the sample frequency as 3 000, and some different width value of the window. From the curves, it can observe the change obviously.

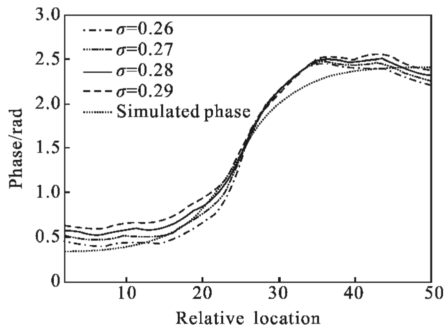

Fig.7 Influence of width of window at threshold value is from 0 to 128, sample frequency is 3 000

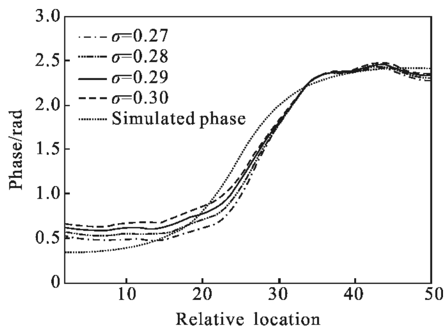

Fig.8 Influence of width of window at threshold value is from 0 to 133, sample frequency is 3 000

(c) The phase unwrapping is frequently needed to construct a continuous phase map from a wrapped phase map. The only difference between them is 2π jumps[8]. Even this method is usually unsuccessful when applied to a noisy wrapped phase map, it had been reduced the noise of whole spectral by set up a threshold. It had to choose an appropriate threshold value to filter the spectral signal, in order to protect the useful information.

The algorithm is mathematically simple and it can be readily combined with commonly used data analysis methods. However, it should note that in our simulation, the other factors are simplified or ignored. In practical experiment, many factors could affect the phase modulation. In order to obtain a better result, it should consider the factors comprehensively.

4 Conclusion

A new signal processing method based on WFT is presented . The numerical simulations are performed to demonstrate the high precision of the phase retrieval from the spectral signal. In order to promote the precision of the signal processing, it had to consider some important factors. During the procedure, it find the width of the window is the key factor. Only choosing the most suitable value, it can achieve a desired and concise differential phase map. From the achieved spectral phase difference, it obtained the detection limit 3.894×10^{-7} RIU. Contrast with the simulated result, the precision of this algorithm is 0.28%, which is considerably higher than achievable by either approach.

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