Signal detection of an optical fiber surface plasmon resonance sensor

Zheng Yan[1], Xing Liyun[1,2], Chang Tianying[1], Wang Min[1], Sun Yufeng[1], Cui Hongliang[1], Liu Ye[1], Zhao Yue[1]

(1. College of Instrumentation & Electrical Engineering, Jilin University, Changchun 130021, China;
2. College of Electrical and Information Engineering, Beihua University, Jilin 132013, China)

Abstract: The optical fiber surface plasmon resonance (SPR) sensor is an advanced and high-precision sensor, used mainly in environmental pollution detection and detection of biopolymers. Firstly, based on the plasmon resonce sensing theory, the estimate of meaning linear model was obtained by a discussion of our experimental results and the system´s data-processing issue. Then, based on the estimate of meaning linear model, a number of groups of a solutions were measured at different times and under the same circumstances and their spectral data was obtained, leading to the estimate of the effective resonance wavelength. Secondly, a wavelet analysis for the SPR reflected spectrum is carried out. The deviation of the resonant wavelength caused by noise was corrected, and the experimental data was filtered by a wavelet analysis, improving the system precision. Parameters impacting the fiber-optic SPR sensor performance were analyzed by theoretical calculation and simulation used Matlab, to optimize the sensing system design. Differences of the refractive index of test solutions such as distilled water, alcohol, etc, have been measured. Our design of the optical fiber SPR sensing systems was proved to be feasible and worked well. The result shows the relationship between the refractive index and SPR wavelength that is well linear within the measurable refractive index range.

Key words: surface plasmon resonance; optical fiber SPR sensor; wavelet denoising
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光纤 SPR 传感器的信号检测及处理

郑 妍[1],邢砾云[1,2],常天英[1],王 敏[1],孙玉锋[1],崔洪亮[1],刘 野[1],赵 越[1]

(1. 吉林大学 仪器科学与电气工程学院,吉林 长春 130021;
2. 北华大学 电气信息工程学院,吉林 吉林 132013)

摘 要:光纤表面等离子体共振(SPR)传感器是目前应用在环境介质检测和生物大分子检测等方面的新型、高精度传感器。首先,以表面等离子体共振传感理论为基础,对系统检测结果进行数据处理,得出采用均值估计的线性模型。在不同时刻与相同环境介质下,检测某一溶液的十组光谱数据并进行

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作者简介:郑妍(1990-),女,硕士生,主要从事光纤 SPR 传感器,棱镜 SPR 传感器、纳米光学与纳米电子学方面的研究工作。Email:zhengyan400356@sina.cn

导师简介:崔洪亮(1956-),男,国家"千人计划"特聘教授,博士生导师,博士,主要从事光纤通信和传感,固态电子及半导体物理和器件,THz 科学技术及应用的研究,纳米光学和纳米电子学等方面的研究工作。Email:hcui@jlu.edu.cn

均值估计,从而得到有效的共振波长。其次,利用小波分析方法进行信号处理,校正了噪声产生的漂移,对光谱信号压缩处理,以提高检测精度。再通过 Matlab 进行模拟仿真优化传感系统性能。并对不同折射率溶液如蒸馏水、酒精等进行检测,得到了良好的光谱响应曲线,证明了在检测范围内折射率和共振波长之间具有良好的线性关系。

关键词:表面等离子体共振;光纤表面等离子体共振传感器;小波去噪

0 Introduction

In 1968, the German physicist Otto studied by surface plasmon resonance and suggested that the effect is actually an attenuated total internal optical reflection. In 1970, Kretschmann proposed a new rough surface perturbation theory, and designed a new equivalent model[1-2]. SPR sensors are usually based on coupling mechanisms based on prisms, optical fibers, and raster types. The surface plasmon resonance effect is an optical phenomena occurring at the physical interface of a metal and a dielectric. Optical fiber surface plasmon resonance sensor features interface that can combines clever novel photochemical sensing mechanisms. Fiber surface plasmon resonance sensor with high sensitivity, miniaturization, connected with the transmission fiber to achieve the advantages of remote data acquisition, which is easy to measure in real-time transmission, small size and high sensitivity [3-7]. According to the principle of SPR excitation effect, the analysis of the relationship between the angle of incidence of the reflected light intensity modulation curve angle, wavelength modulation, intensity modulation, phase modulation method of four kinds of methods. Current widespread use is the angle modulation and wavelength modulation method, intensity modulation error is larger, phase modulation method of maximum sensitivity, but requires a series of high-frequency circuits[8]. In addition, surface Plasmon resonance technology needs further research on the chemical, physical, biological sensing, and actively explore applications in other fields.

In this paper, according to the principle of surface plasmon resonance based on MATLA B data processing solutions with different refractive indices, such as distilled water, alcohol, etc. were tested. We have designed a fiber surface plasmon resonance sensor system with a good response, and showed that the refractive index and the resonant wavelength has a good linear relationship in the range of measurement.

1 Fiber surface plasmon resonance sensor basic principles and structure

1.1 Fundamental

The basic structure of a fiber surface Plasmon resonance sensor includes the sanitation film, the core and the layer structure and environmental media. Fiber optic SPR sensor is sensitive to the refractive index of the ambient medium, different concentrations of the same solution of the respective refractive indices, the resonant wavelength of the spectrum when the SPR sensor changes the refractive index and the depth of the resonance will change. Toward the optically sparse medium $n_2<n_1$ from optically denser medium according to the law of refraction, light waves when, $\sin\theta_1/\sin\theta_2=n_3/n_2<1$, this time there is no refraction of the incident light which is completely reflected back to the incident medium, a phenomenon known as total internal reflection, the corresponding angle of incidence θ_0 known as the critical angle. And the corresponding critical angle is $\theta=90°$. Because of the complex dielectric properties of the metal itself, resulting in the gold film and the core of the interface will penetrate into the metal part of the sensitive film, which will exponentially reaches a certain depth to form evanescent wave. Evanescent wave at the interface between the metal film and the air or solution still works. Fiber optic SPR sensor probes the structure shown in Fig.1.

Therefore, the wave vector of the evanescent wave is K_z.

$$K_z=\frac{w}{c}\sqrt{\varepsilon_1}\sin\theta_0 \tag{1}$$

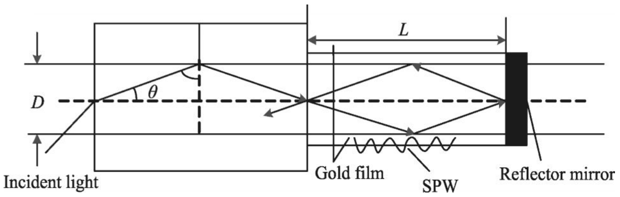


Fig.1 Structure of fiber optic SPR sensor probe

Since the wavelength of incident light in the experiment we used generally in the visible and near-infrared region, and then in the complex permittivity of the metal thin film is much greater than the imaginary part of the live. Metal dielectric constant is represented by $\varepsilon_2\cdot\varepsilon_2=\varepsilon_c+i\varepsilon_l$. And there $|\varepsilon_c|\geqslant\varepsilon_i$, proportional to the refractive index of the medium and the dielectric constant's square. $\varepsilon\propto n^2$. Thus, according to the Maxwell equations and the metal complex dielectric properties can be obtained by formula (2):

$$\sin\theta_{spr}=\sqrt{\frac{\varepsilon_c{*}n_2^2}{\varepsilon_c+n_2^2}}/n_0 \tag{2}$$

Where n_0 is the core; n_1 is metal; N_2 is the refractive index of the surrounding medium; ε_1 is the core; ε_2 is metal; ε_3 is the dielectric constant of the surrounding medium. From formula (2), it shows that the resonance angle θ_{spr} very sensitive to changes in n_0、n_2 and ε_c. When n_0 and ε_c determine, θ_{spr} liquid medium resolution up 3.5×10^{-5}[9].

1.2 Components of the fiber optic SPR sensor system

Fiber optic SPR sensor system shown in Fig.2, fiber optic SPR sensor based on gold film shown in Fig.3, gold thickness of 50 nm[10], gold layer reflector, probe

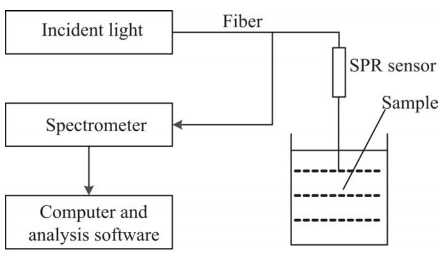


Fig.2 Fiber SPR system

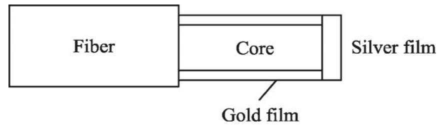


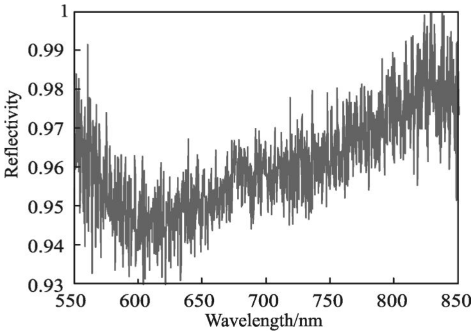
Fig.3 Structure of fiber SPR sensor

length 20 mm [11], fused quartz core diameter of 600 μm, the light source is HL-2000-HP broadband light source, HR4000 fiber optic spectrometer.

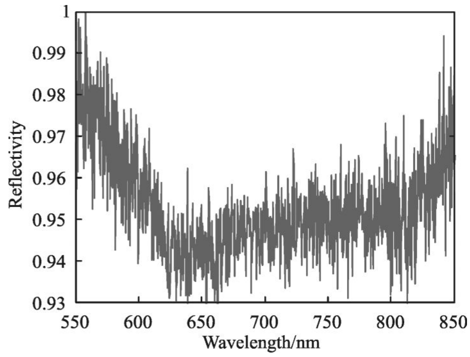
2 Experimental data analog processing using Matlab

Through Matlab analog to process the affect sensor performance parameters, since the refractive index of the optical fiber SPR sensor is sensitive to the ambient medium, the refractive index changes when the SPR sensor resonance wavelength resonance spectroscopy and depth will change accordingly. Solutions of different concentrations of the respective refractive indices are not identical, if the refractive index thereof and the resonance wavelength of the resonance to determine the relationship with the depth, measuring these two parameters can be calibrated to the concentration of the test solution. Under given conditions of the detection system, the refractive index of water is 1.333 3, and the refractive index of alcohol is 1.390 0, and the refractive index of the NaCl concentration of 90% is 1.334 7, the resonant wavelength to be measured nearly 620 nm, 650 nm and 620 nm. However, due to the presence of noise, we must take a sufficiently wide range of signal processing, the system considers the detection range of 550-850 nm, the following Fig.4 (a), (b) and (c) are respectively ten sets of original spectral data of water, alcohol, and a graph of the mean NaCl treatment.

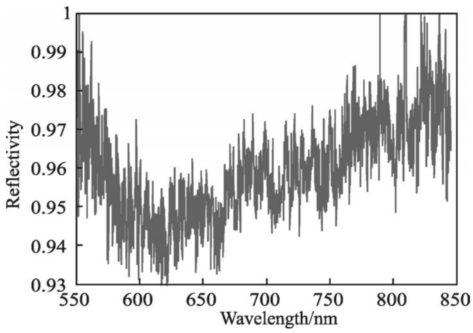
For mean curves of Fig.4, at a constant ambient temperature, if the measured object is ignored molecular vibrations caused perturbation should be a smooth curve. SPR is not smooth because of the optical fiber sensor which due to the influence of noise when the system allows the detection result of the detection in the presence of volatile data, although the experimental data processing



(a) Mean curve of water from ten groups of original spectral data



(b) Mean curve of alcohol from ten groups of original spectral data



(c) Mean curve of NaCl from ten groups of original spectral data

Fig. 4 Mean value curve ten sets of spectral data

means, but the curve is still not very smooth, because it is still difficult to accurately determine the resonant wavelength, which need further estimates.

3 Noise of the fiber optic SPR sensor system

The main types of fiber optic SPR sensor noise detection system includes a light source noise, spectrometer CCD noise, environmental perturbation noise and devices coupled noise. Noise makes the measured spectral reflectance curve SPR glitches, which cannot accurately measure the resonance wavelength. Kurtosis method using skewness can also determine the nature of the main noise is Gaussian white noise[12].

According to the composition and fiber optic SPR sensor test mode detection system, by setting meet:

$$MIN[S_R(n,\lambda)]>>MIN[N_{CCD}(n,\lambda)+N_L(n,\lambda)] \tag{3}$$

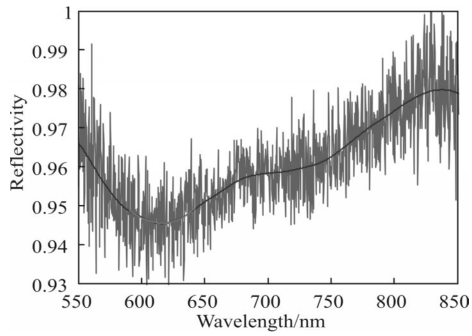
Thus

$$Y(n,\lambda)\cong\frac{S_L(n,\lambda)}{S_R(n,\lambda)}+\frac{N_L(n,\lambda)+N_{CCD}(n,\lambda)}{S_R(n,\lambda)}=S(n,\lambda)+N(n,\lambda) \tag{4}$$

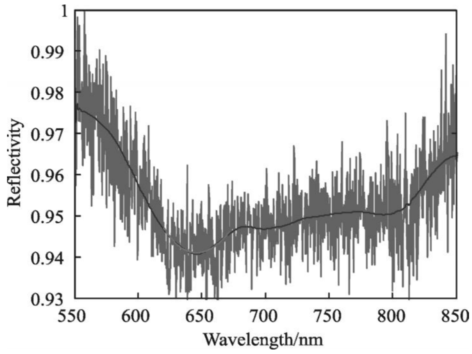
Where $Y(n,\lambda)$ is measurement data; $S_R(n,\lambda)$ is reference light signal; $N_L(n,\lambda)$ is noise source; $S_L(n,\lambda)$ is reflected light signal; $N_{CCD}(n,\lambda)$ is CCD noise; $N(n,\lambda)$ is overall noise signal; $S(n,\lambda)$ is real test signal; n is sampling time; λ is wavelength.

Fiber optic SPR sensor detection system is determined by detecting the resonance wavelength of the measured object information, so only a small area of concern includes the resonant wavelength do noise analysis. This will help to improve the data processing speed, and it will not affect the detection accuracy.

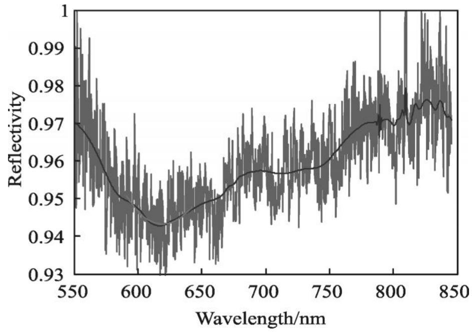
Such as water and alcohol, detection system under given conditions, the refractive index of water is 1.333 3, the refractive index of alcohol is 1.390 0, and the refractive index of the NaCl concentration of 90% is 1.334 7, the resonant wavelength to be measured nearly 620 nm, 646 nm and 620 nm. However, due to the presence of noise, we must take a sufficiently wide range of signal processing, the system considers the detection range of 550–850 nm, the following Fig.5 (a), (b) and (c) are respectively ten sets of original spectral data of water, alcohol, and a graph of the mean NaCl treatment.



(a) Spectral data of ten groups of water mean curve graph and the graph of wavelet denoising



(b) Spectral data of ten groups of alcohol mean curve graph and the graph of wavelet denoising



(c) Spectral data of ten groups of NaCl mean curve graph and the graph of wavelet denoising

Fig.5 Mean curve ten sets of spectral data contains wavelet denoising graph

4 Using wavelet denoising method to undo noise of Gaussian whitenoise and do average operation

4.1 Wavelet denoising principle

The main characteristic of the wavelet transform is a linear decomposition and partial double time domain and frequency domain, even the signal can be decomposed into a linear time and characterize different frequency components [13]. As shown in Fig.6 which is the wavelet transform denoising flow diagram. When the signal wavelet decomposition, noisy part consists mainly of high frequency wavelet coefficients, and thus can be used to form a threshold, such as the threshold of wavelet coefficients for processing, and then reconstruct the signal can achieve noise cancellation purposes.

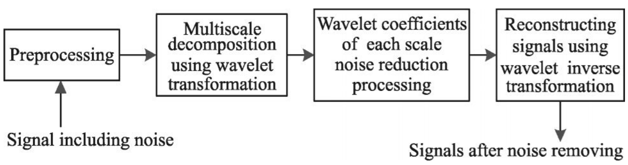


Fig.6 Wavelet transform denoising flow diagram

4.2 SPR spectroscopy wavelet denoising

Through analysis, we know that fiber optic SPR sensor is often concern the intensity of the SPR resonance spectrum and the size of the wavelength of the resonance peak, and therefore can be removed by calculating the intensity of the resonance peak wavelength and the resonance SPR noise spectral curve. Since entering the noise is different, the results of each calculation are different, to exclude an individual, this paper three solutions to the noise generated by different refractive index measurements performed 10 times during the simulation of wavelet denoising on demand strength and resonance wavelength was averaged .

This paper uses the discrete wavelet coefficients provided in MATLAB: Daubechies wavelet coefficients (db1-10) and Symlets wavelet coefficients (Symlet7, 11, 14, etc.) wavelet denoising noisy signals, and using Rigrsure threshold selection rules and 'Sln' retune the threshold method to prove the use of thresholding wavelet function db4 and Sym11 correction function can be better due to the noise generated by the resonance wavelength shift, that as much as possible to remove noise, and possible retains much of the original signal information.

For a given threshold denoising method, it was mainly doing the discretization operation of the wavelet transform for processed signal, and determining a threshold that obtain the wavelet coefficients to select the threshold .The so-called threshold selection includes hard threshold and soft threshold two categories, their return signals respectively:

$$Y=\begin{cases} x & |x|>T \\ 0 & |x|\leqslant T \end{cases};\quad Y=\begin{cases} \mathrm{sign}(x)(|x|-T) & |x|>T \\ 0 & |x|\leqslant T \end{cases}$$

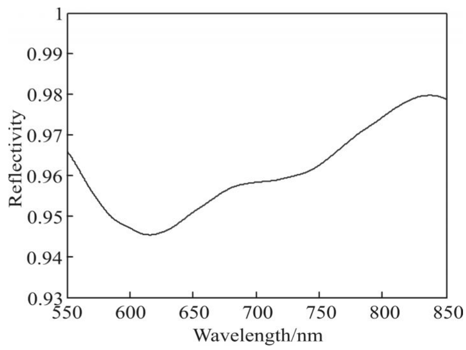
In which T was given by the threshold, X was the wavelet transform coefficient, Y was after the wavelet coefficient threshold value.

Wavelet analysis was generally divided into three methods, acquiescent threshold value, given threshold value and constraint denoise processing respectively.

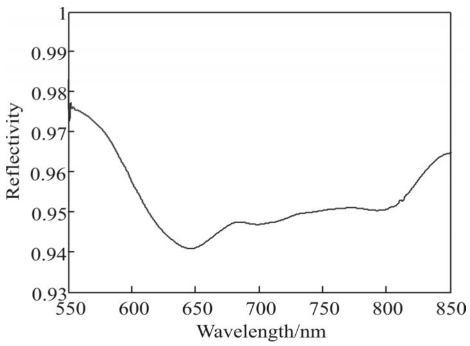
Among them, the constraint denoising method was easy to get smoother video signal after denoising , but it could be prone to loss the phenomenon of important signals , so it was not suggested to adopt generally. The credibility of given threshold denoising value processing method in treatment of actual denoise was higher than the acquiescent threshold denoising processing. Therefore, this paper used ‘Rigrsure’ threshold selection rules and ‘Sln’ retune the threshold method.

By using Matlab processing, and then remove noise by thresholding wavelet method can eliminate a lot of irrelevant information spectral data, so as to achieve the purpose of compressed data for storing data, handling convenience, to reduce the computational work volume, improve work efficiency. The results shown in Fig.7 (a), (b) and (c) shows the water, alcohol and NaCl on the spectral data of the mean estimate of wavelet de-noising linear curve.

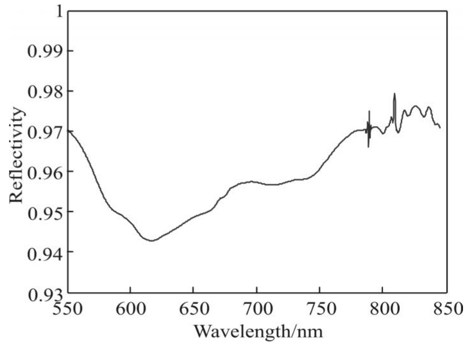
Water, alcohol and NaCl on wavelet de-noising mean spectral data comparing the estimated linear curve on the same graph, obtained due to the refractive index of the fiber optic SPR sensor sensitive to the ambient



(a) Mean estimate graph after water wavelet denoising



(b) Mean estimate graph after alcohol wavelet denoising



(c) Mean estimate graph after NaCl wavelet denoising

Fig. 7 Mean spectral curve of wavelet denoising

medium, different concentrations of each of the refractive index of the solution are not the same when the refractive index change of the resonant wavelength and resonance spectroscopy depth will change accordingly; If they resonant wavelength and the refractive index has to determine the depth of the relationship between the resonance, by measuring these two parameters can be used to calibrate the measured concentration of the solution.

When seen from the results of data processing, only the signal level decomposition may be obtained while relatively high signal, but this signal will not completely denoising, noise will still be present, so one decomposition is unreasonable. The higher SNR of the signal, after denoising of RMSE is smaller, denoising effect is better. Therefore, decomposition layers selected for five layer can obtain good effect, amount of calculation is more suitable. As shown in Fig.8.

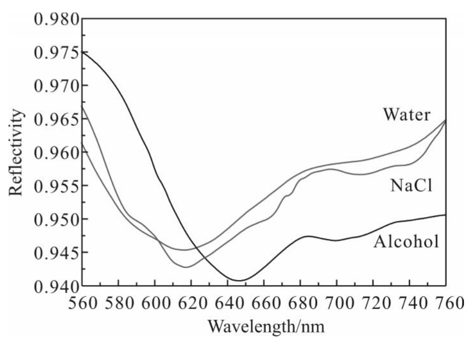


Fig.8 Spectrum diagram of the water, alcohol and NaCl of five layer decomposition wavelet denoising

By analyzing with the relevant literatures, we use of one-dimensional wavelet analysis to compress spectrum signal[14]. Because a regular spectral signal is composed by a relatively small amount of low−frequency coefficients data and several layers of a high frequency coefficients. We choose the low −frequency coefficients has a requirement that needs to select the low −frequency coefficients in a suitable decomposition layers.

5 Conclusions

This work established systems for fiber optic SPR signal model, and the entire system noise analysis, the noise of the high frequency signals. In the fiber surface plasma wave sensor signal processing part , through the fiber optic SPR detection system signal model analysis, wavelet thresholding method chosen threshold de−noising and data compression for its SPR reflection spectra . Experiments show that the method of correcting the detection system due to the noise generated by the resonance wavelength shift and reduce the amount of storage at the same time eliminate most of the noise signal, reducing the computational effort, making the fiber optic SPR detection systems meet the needs of practical applications. On this basis, the use of wavelet thresholding method in the determination of the application of SPR spectrum is carried out in a theoretical study, and an experimental verification of fiber SPR detection system characteristics in environmental media of different refractive indices was performed.

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