Spectrum Calibration and Processing Research of Thin-Film Thickness Wideband Monitoring System

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Abstract: In thin-film thickness wideband monitoring system, the monitoring effectiveness depends on the real-time and accurate measurement of the spectrum. To achieve the correct spectral signal in real-time, by analyzing the configuration of the spectrometer, the proper slit width of 0.14 mm was determined, the spectrum calibration function was achieved; The strong background noise was eliminated by subtracting the signal in the dark state from the signal in the adjacent bright state to the same pixel; the random noise was suppressed by the wavelet threshold optimization algorithm. Experimental result showed that the spectral resolution was less than 2 nm and the root-mean-square error of the wavelength calibrated was 0.037 nm; Background noise and random noise were well suppressed and the details of the spectrum signal were reserved, maximum of the peak error and the peak location of the spectral signal was 1.0 % and 0.3 % respectively. This improves the monitoring accuracy, thin film thickness monitoring error is less than 10^-3. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Real-time spectrum measurement, Thin-film thickness, Spectral resolution, Spectral calibration, Spectral noise processing.

1. Introduction

With the enhancement of complexity and precision of optical thin-film, the conventional monitoring methods couldn’t meet the requirement. Recently a visual and usable technology gradually becomes mature and begins to be applied, which is the thin-film thickness wideband monitoring technology [1, 2]. In thin-film thickness wideband monitoring system, the thin-film thickness monitoring is realized by measuring precisely the wide spectrum of optical thin-film and calculating the difference between the spectral curve designed and the measured in real-time during the course of thin-film deposition [3, 4], when the difference is up to minimum the monitoring process ends. Traditionally, acquisition of the spectrum is implemented by means of alternate rotation of monochromator’s grating driven by the stepper motor and detection using the photomultiplier tube. However the information of one wavelength can be measured once in this way and the online spectrum measurement can’t be quickly finished [5]. Recently, CCD is widely used for the spectrum measurement system because of its real-time transmission and self-scanning. Herein linear CCD detected the spectrum dispersed by the grating spectrometer [5], then converted the spectrum into serial-output electric signal. The computer received this signal at the speed of millisecond and performed data processing for displaying the spectral curve in real-time. The complexity of mechanical scanning was avoided and the problem of the real-time spectral...
scanning was solved by this method. In this paper, for correctly measuring the spectrum, the grating, CCD and the slit width of the spectrometer were determined for meeting the requirement of spectral resolution of 2 nm, the spectral calibration function was established for obtaining the correct location of wavelength; Then the strong background noise was eliminated by subtracting the signal in the dark state from the signal in the adjacent bright state to the same pixel, random noise was processed by the wavelet threshold optimization algorithm. This ensured the monitoring effectiveness.

2. Analysis of Spectrum Resolution

2.1. Spectral Measurement Principle

As illustrated in Fig. 1, the spectrum measurement part of the system was shown in dashed-line frame. A visible beam emitted from light source was modulated by a chopper, entered into vacuum chamber and was incident on the sample monitored; the transmitted light exited from vacuum chamber, then passed through a fiber optic cable and arrived at the entrance slit of the fiber spectrometer. The divergent light going through the slit was collimated by a concave mirror and directed onto a grating. The grating dispersed the spectral components of the light at slightly varying angles, which was then focused by a second concave mirror called as the imaging mirror and imaged onto the linear CCD. The optical signal was converted into electrical signal which was digitized and read out to a computer, finally the spectrum curve measured was displayed. The spectrum measurement was completed. By data processing of the computer, when the difference between the spectrum curve designed and the measured was minimum, the deposition course ended and thin-film thickness achieved the desired goal [3, 4].

![Fig. 1. Schematic diagram of thin-film thickness wideband monitoring system.](image)

2.2. Analysis of Spectrum Resolution

For spectrum measurement, the spectrum resolution was an important parameter affecting measurement precision. The requirement of this system was the spectrum resolution of 2 nm and the dispersive spectrum region of 400 nm to 800 nm. There are three main factors that determined the spectral resolution of a spectrometer: the diffraction grating, the detector and the slit. The diffraction grating was a dispersive element, whose resolution was given by

\[ R_s = \frac{\lambda}{\delta \lambda} = mN, \]  

where \( \lambda \) is the wavelength dispersed, \( m \) is the diffraction order, \( N \) is the total number of grooves on the grating. The minimum wavelength difference that can be resolved by the diffraction grating was given by

\[ \delta \lambda = \frac{\lambda}{mN}, \]  

in terms of Rayleigh criterion [6], the linear dispersion rate of the grating was expressed by the equation:

\[ \frac{dl}{d \lambda} = \frac{mf_z}{d \cos \theta}, \]  

where \( f_z \) is the focal length of the imaging mirror, \( d \) is the groove period, \( \theta \) is the diffraction angle of the specific wavelength. The diffraction grating determined the total wavelength range of the spectrometer, the highest resolution of the system depended on the grating resolution because the grating was fixed [6, 7]. The spectrum dispersed by the grating was detected by linear CCD array which located at the focal plane of the imaging mirror, because the pixel of CCD had certain size, the pixel resolution, which was defined as the minimum wavelength difference that can be resolved by CCD array was given by

\[ \Delta \lambda = 2r \cdot \frac{d \lambda}{dl}, \]  

where \( \frac{d \lambda}{dl} \) is the reciprocal of linear dispersion of the grating, \( r \) is the distance between the center of the adjacent pixel of CCD [7, 8]. From this equation, the spectral resolution of CCD array decreased with the size of CCD pixel increase. Considering that the maximum spectral range \( (\lambda_{max} - \lambda_{min}) \) can be calculated based upon the detector length, it is expressed as

\[ \lambda_{max} - \lambda_{min} = l_D \cdot \frac{d \lambda}{dl} = W_p \cdot n \cdot \frac{d \lambda}{dl}, \]  

where \( l_D \) is the detection length of CCD, \( W_p \) is the pixel width, \( n \) is the total numbers of pixels. So the
A grating of 300 lp/mm is chosen, with the linear dispersion of 1/18 mm/nm, the model of CCD is TCD1251UD with 2700 pixels and the pixel width of 11 μm. According to Equation (5), the spectral range calculated was 534.6 nm, which is more than 400 nm and met the requirement. The pixel resolution was 0.396 nm, it can also meet the requirement. After CCD array and the grating were determined, the overall spectral resolution of the system directly depended on the slit width. Because the incident slit located at the focus plane of the collimating mirror, the width L of its image locating at the focus plane of the imaging mirror was given by

\[ L = l_1 + l_2 = \frac{\cos i f_2}{\cos \theta f_1} l + \frac{\lambda}{D} f_2, \quad (6) \]

where \( l \) is the slit width, \( l_1 \) is the width of the slit geometrical image, \( l_2 \) is the width of the diffraction image, \( f_1 \) is the focal length of the collimating mirror, \( i \) is the incident angle of the grating, \( \lambda \) is the wavelength of the incident light. The spectrum width corresponding to the image width of the slit was given by

\[ \Delta \lambda_s = \frac{d \lambda}{d l} \cdot L, \quad (7) \]

the overall resolution \( R_s \) of the system was expressed as

\[ R_s = \frac{\lambda}{\Delta \lambda_s} = \frac{\lambda}{L} \frac{d l}{d \lambda}, \quad (8) \]

From Equation (8), \( R_s \) is inversely-proportional to the slit width [7, 9]; In order to increase the overall resolution, the slit width need be reduced. But the light flux that entered the optical bench from the slit was written as

\[ \Phi = \frac{lhWH \cos \theta}{f_1 f_2}, \quad (9) \]

where \( W \) and \( H \) are the width and the height of the grating respectively, \( h \) is the slit length [7]. From Equation (9), after the grating was decided, the slit became narrower and the incident light flux of the optical bench became weaker, which would make SNR of the system decrease. Because of the diffractive effect, when the slit width decreased below a certain extent, the resolution couldn’t almost increase, however the loss of the light flux was very serious. From the above analysis, the slit width had the perfect value. Considering that the requirement of the overall spectrum resolution was less than 2 nm, the spectral lines of 577 nm and 579 nm of mercury spectrum lamp, whose power equaled to the light source of the monitoring system, were used for determining the slit width. Two spectral lines variation with the slit width is shown in Fig. 2.

### Table 1. Relationship of the slit width and the intensity ratio.

<table>
<thead>
<tr>
<th>Slit width (mm)</th>
<th>Intensity ratio</th>
<th>Slit width (mm)</th>
<th>Intensity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>9.6</td>
<td>1.8</td>
<td>1.74</td>
</tr>
<tr>
<td>1.5</td>
<td>3.4</td>
<td>1.9</td>
<td>1.66</td>
</tr>
<tr>
<td>1.6</td>
<td>3.21</td>
<td>2.0</td>
<td>1.45</td>
</tr>
<tr>
<td>1.7</td>
<td>1.99</td>
<td>2.2</td>
<td>1.17</td>
</tr>
</tbody>
</table>

The ratio of the peak intensity to the valley intensity represented the spectral resolution, i.e. bigger its value became, higher the resolution was [7]. The data are shown in Table 1. According to compromise on the incident light flux and the spectral resolution, the proper slit width confirmed was 0.14 mm.

### 3. Spectrum Calibration

The spectral lines dispersed by the grating corresponded to the different pixels of CCD array, so the relationship of the pixel ordinal and the wavelength, namely the spectrum calibration function, must be established. In use of the standard light source, its characteristic spectral lines were utilized to obtain the corresponding ordinal numbers of the pixels [10]. In fact, because of the non-linearity of the grating dispersion, the spectral range accepted by each pixel of CCD array was different and the spectrum calibration function was non-linear. The polynomial fitting approach was adopted [11]. When the experiment was done, the standard light source chosen was low pressure mercury lamp whose
characteristic spectral lines used were 404.7 nm, 435.8 nm, 546.07 nm, 576.96 nm, 579.1 nm, the experimental data was shown in Table 2. Then the wavelength was considered as dependent variable, the ordinal number of the pixel was independent variable, by least-square polynomial fit, the spectrum calibration function was created and written as

\[ \lambda_p = -3.4277 \times 10^{-3} n^3 -3.3863 \times 10^{-2} n^2 + 0.2938 n + 346.4384, \]

where \( \lambda_p \) is the wavelength calibrated, \( n \) is the ordinal number of the pixel. The curve fitted was shown in Fig. 3, the data fitted was shown in Table 3, the root-mean-square error of the wavelength was 0.037 nm. The spectrum calibrated of mercury lamp was shown in Fig. 4. For verifying the spectrum calibration function, He-Ne laser of 632.8 nm and the sodium lamp of 589.3 nm were used, the root-mean-square error of the wavelength is 0.06 nm. This calibration method could be adopted and met the requirement of the spectrum resolution of 2 nm during the course of thin-film deposition.

### Table 2. Relationship between the characteristic wavelength and the corresponding ordinal number of the pixel.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Ordinal number of the pixel</th>
<th>Wavelength (nm)</th>
<th>Ordinal number of the pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>366.5</td>
<td>67</td>
<td>546.07</td>
<td>749</td>
</tr>
<tr>
<td>404.66</td>
<td>203</td>
<td>576.96</td>
<td>882</td>
</tr>
<tr>
<td>435.8</td>
<td>316</td>
<td>579.1</td>
<td>892</td>
</tr>
</tbody>
</table>

### Table 3. The result fitted and error of the characteristic spectral line.

<table>
<thead>
<tr>
<th>Ordinal number of the pixel</th>
<th>Standard wavelength (nm)</th>
<th>The wavelength fitted (nm)</th>
<th>Error (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>203</td>
<td>404.66</td>
<td>404.6611</td>
<td>0.0011</td>
</tr>
<tr>
<td>316</td>
<td>435.8</td>
<td>435.7980</td>
<td>0.002</td>
</tr>
<tr>
<td>749</td>
<td>546.07</td>
<td>546.077</td>
<td>0.007</td>
</tr>
<tr>
<td>882</td>
<td>576.96</td>
<td>576.8986</td>
<td>0.0614</td>
</tr>
<tr>
<td>892</td>
<td>579.1</td>
<td>579.1553</td>
<td>0.0553</td>
</tr>
</tbody>
</table>

Fig. 3. The curve fitted.

Fig. 4. Diagram of the characteristic spectral line of the mercury lamp after calibration.

### 4. Noise Processing of the Spectral Signal

In order to realize the effective measurement of the spectral signal, not only the spectral resolution and the wavelength positioning accuracy were high enough, but also the measurement precision should be ensured. There were two factors affecting the measurement precision, one was the strong background noise produced by the ambient light in vacuum during the process of thin-film deposition, the other was the intrinsic noise of CCD array. The following is the method used for processing of this noise.

#### 4.1. Method Used for Processing the Background Noise

Because CCD array detected light intensity on the condition of the strong ambient light, but CCD array couldn’t differ the monitoring signal light from the ambient light according to the light intensity, output of CCD array distorted after the monitoring spectral signal detected by CCD array. This seriously affected the accuracy of the spectral curve measured and made the monitoring work failure. Background noise must be eliminated.

During the course of the thin-film deposition, the main difference of the signal light and the ambient light was frequency. The variation of the signal light had unique monotonicity and the range of time spent depositing the material of each layer was from 10 s to several minutes according to deposition material and technological parameter, so the signal light could be considered as the alternating signal with very low-frequency; The ambient light was produced by the directive deposition of the material, it could be thought as the random signal with high-frequency. Based on the above analysis, considering that the signal power of each pixel increased by a factor of \( m^2 \) and its noise power increased by a factor of \( m \) when the integral time was extended from \( T \) to \( mT \), so the power ratio of signal to noise increased a factor of \( m \). In use of signal repeatability and noise randomness, signal and noise accumulated
respectively at a specified integral time for reducing the effect of the background noise. On the other hand, when the intensity of the spectral signal was too high, the output signal of CCD array reached saturation; when the intensity of the spectral signal was too low, the overall ratio of signal to noise extremely decreased [13, 14]; When the strong spectral signal was detected by CCD array, the integral time would be shortened; when the signal was weak, the integral time would be extended. As such the information loss could be reduced and the peak location of the spectral line wasn’t influenced. So according to the characteristics of the coating deposited, the integral time was decided on basis of $SNR$ and the intensity of the spectral signal.

For effectively obtaining the spectral signal, firstly the incident cone angle of the optical receiving system should be decreased for reducing the ambient light incidence in the optical receiving system. However due to additivity of the light energy, the ambient light couldn’t be completely eliminated by the improvement of the optical receiving system, then the chopper of the duty cycle of 1:1 was driven by the stepper motor for modulating the beam emitted from the light source into the light beam alternated with darkness, the highest modulation frequency was 10 Hz. The output of CCD array is obtained in the bright and dark state with the same integral time for several times. The output included three parts in the bright state, one was produced by the ambient light, another originated from the monitoring light, the last resulted from the dark current of CCD array. The output included two parts in the dark state, one was produced by the ambient light, the other resulted from the dark current of CCD array. For the same pixel, the output obtained in the bright state subtracted the output obtained in the dark state to eliminate background noise and the dark current of CCD array after they take the average [15]. Because pace, revolution and angle of the stepper motor were known and controlled, the bright and dark state of the light beam modulated could be identified.

Three-state gate is utilized when the light beam modulated was in the bright or dark state. Three-state gate is set high level, the output of CCD array was allowed to transmit to data acquisition card, simultaneously the mark is set for making a distinction of data in the bright and dark state. When the light beam modulated lied in partially bright and partially dark state, three-state gate was set low level, the output of CCD array couldn’t pass through three-state gate, data are invalid. So the signal in the bright and dark state is sampled accurately, CCD array and data acquisition card matched correctly. For ensuring synchronization of the chopper and data acquisition card, the microprocessor was used for controlling the stepper motor and three-state gate to accurately achieve data in the light and dark state. The whole working process is shown in Fig. 5.

For verifying the feasibility of the above method, the integral time of CCD array was set as 8 ms, the spectrum was obtained during the course of TiO$_2$ deposition on the substrate of glass, as shown in Fig. 6. Obviously there were linear peaks in the spectrum curve, because the ingredients of the deposition material had some changes during the course of deposition, the light produced by them would result in the sudden change at some wavelengths of the spectrum curve. Then under the condition of the same integral time, the signal was acquired in the adjacent dark state, as shown in Fig. 7. Lastly the intensity of the spectral signal at each wavelength in Fig. 6 substrates the intensity of background signal in Fig. 7, the result is shown in Fig. 8.
4.2. Method Used for Processing the Random Noise

For the random noise of the spectral signal, according to the property which was each scale difference of the signal and the random noise on the condition of wavelet transform [16, 17], wavelet threshold optimization algorithm was designed to filter out wavelet coefficient of noise and reserve the signal details.

For the spectral signal measured, it was thought to be one dimensional model of the signal including noise. Supposed that it was expressed as

\[ f(i) = s(i) + n(i), \]

where \( s(i) \) is the original signal, \( n(i) \) is the Gaussian white noise whose variance is \( \sigma^2 \) and who obeyed \( N(0, \sigma^2) \). Wavelet threshold filtering method was the following:

1. Performing wavelet transformation:

\[ w = W(f), \]

after transformation, wavelet coefficient was given by

\[ w_f = w_s + w_n, \]

2. Processing wavelet coefficient of the signal and noise, it can be written as

\[ w(i) = D(w, f(i)), \]

3. Performing the wavelet inverse-transformation as

\[ \hat{f}(i) = W^{-1}\{w(i)\}, \]

and reconstructing the signal, the result was given by [16]

\[ \hat{f}(i) = \hat{s}(i) + \hat{n}(i), \]

The key was how to treat wavelet coefficient in the course of processing. Because wavelet coefficient of the original signal was relatively big and that of noise was relatively small, the appropriate threshold need be determined to make the wavelet coefficient less than the threshold set to zero and the one more than the threshold reserved [18]. Noise is suppressed. Presently the general threshold function was proposed by Donoho and Johnstone, which was divided into the hard-threshold and the soft one. That is the hard-threshold function was given by

\[ \hat{w}(i) = \begin{cases} w(i) & |w(i)| \geq T \\ 0 & |w(i)| < T \end{cases}, \]

and the soft one was given by

\[ \hat{w}(i) = \begin{cases} \text{sign}[w(i)]|w(i)| - T & |w(i)| \geq T \\ 0 & |w(i)| < T \end{cases}, \]

where \( w(i) \) and \( \hat{w}(i) \) are the wavelet coefficient before de-noising and after that respectively. Sign was the symbol function, the threshold was written as

\[ T = \sigma \sqrt{2 \log N}, \]
where $\sigma$ was root-mean-square error of noise, which was the estimate value of noise level, $N$ was length of signal [16, 17]. The disadvantage of hard-threshold is to produce some interruption at some points, soft-threshold was extension of hard-threshold and it could make the discontinuous points of the boundary contract to zero on basis of hard-threshold, so the reconstruction signal became smooth.

Donoho threshold de-noising could isolate most of the signal from noise, but when the amplitude of the signal was similar to or less than that of noise this part of the signal could be all filtered out as noise, so the partial information of the signal was lost. Because of this, Donoho threshold de-noising should be improved.

Because the signal and the random noise were performed by wavelet transformation, the modulus value of the former’s wavelet coefficient became large and that of the latter became small when the dimension increased [19, 20]. If $(m,n)$ represented binary wavelet transform at the scale of $m$ and $n$ showed that the signal was performed by the wavelet transform with the layer of $n$, the correlation operation [21] was carried out between transformation values at the adjacent scales, namely

$$corr(m,n) = w(m,n) \times w(m+1,n),$$

then normalization,

$$k(m,n) = corr(m,n) \sqrt{Pw(m)/Pcorr(m)} / w(m,n),$$

$$Pw(m) = \sum_{n} w(m,n)^2,$$

$$Pcorr(m) = \sum_{n} corr(m,n)^2,$$

For signal component

$$corr(m,n) \sqrt{Pw(m)/Pcorr(m)} > w(m,n),$$

then $|k(m,n)| > 1$;

For noise component

$$corr(m,n) \sqrt{Pw(m)/Pcorr(m)} < w(m,n),$$

then $|k(m,n)| < 1$; so $|k(m,n)|$ is used for distinguishing signal and noise and was introduced into the threshold function. Let the micro-alignment factor $g(m,n)$ as

$$g(m,n) = h \times |k(m,n)|,$$

where $h$ is the constant less than 1. The new threshold is supposed as

$$T'(m,n) = \sigma \sqrt{2 \log N} / g(m,n).$$

When $g(m,n) > 1$, $T'(m,n)$ is less than Donoho threshold $T$, which was beneficial to transit the signal component of the small amplitude; When $g(m,n) < 1$, $T'(m,n)$ was more than Donoho threshold $T$, which was favorable to reject noise component. According to this property, the micro-alignment factor $g(m,n)$ was set reasonably to better distinguish the signal from noise and improve the effect of Donoho threshold de-noising. The constant $h$ affected on the action of $g(m,n)$, If $h$ was too big, $T'(m,n)$ would be too small, which increased possibility of noise reserved and probability of false prediction; If $h$ is too small, the micro-alignment action of $g(m,n)$ wasn’t good, the signal whose amplitude was similar to or less than noise was difficultly reserved and the probability of the truth refused was increased. So the constant $h$ must be reasonable, which could reflect the feature of noise. So as to determine the constant $h$, the monitoring signal of the system was modulated into sinusoidal wave of 1000 Hz and was detected by PMT for better analyzing the random noise, the result of the real-time measurement was shown as Fig. 9. Then the simulation experiment was done by Matlab, the random noise is introduced into the sinusoidal signal, the original ratio of signal to noise was decided as 18.9 db in terms of the monitoring signal. Sym4 wavelet was chosen to process this signal by six-layer wavelet decomposition, then de-noising was performed by the improved wavelet threshold optimization algorithm, the ratio of signal to noise corresponding to different $h$ was shown as Table 4.

<table>
<thead>
<tr>
<th>$h$</th>
<th>0.1</th>
<th>0.3</th>
<th>0.35</th>
<th>0.4</th>
<th>0.45</th>
<th>0.5</th>
<th>0.6</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N (db)</td>
<td>11.1</td>
<td>14.2</td>
<td>15.1</td>
<td>16.2</td>
<td>16.0</td>
<td>15.8</td>
<td>14.7</td>
<td>13.1</td>
</tr>
</tbody>
</table>

From Table 4, when constant $h$ is equal to 0.4–0.5, the signal to noise ratio is relatively higher and the difference is very small. Based on this conclusion, the measured signal is filtered when $h = 0.45$, the result is shown as Fig. 9.

![Fig. 9. Monitoring signal including noise detected by PMT.](image-url)
relatively higher. Based on this conclusion, when $h=0.45$ the monitoring signal was filtered by wavelet threshold optimization algorithm, the result was shown as Fig. 10.

Fig. 10. The signal processed by filter when $h=0.45$.

Lastly the real-time measurement was implemented during the course of single thin-film deposition of TiO$_2$ on the substrate of $K_9$ glass, the spectral signal was processed by the wavelet threshold optimization algorithm. The comparative results were shown as Fig. 11 and Fig. 12. Seen from Fig. 12, not only the spectral curve measured became smooth, but also the details could be reserved. Especially the peak value and the peak location were reserved, the error are shown as Table 5. It could be concluded that the signal measured was effectively isolated from the random noise by this algorithm and the effectively spectral information was reserved.

Table 5. Error of the peak value and the peak location after the spectral signal was processed by the wavelet threshold optimization algorithm.

<table>
<thead>
<tr>
<th>Peak</th>
<th>Peak 2</th>
<th>Peak 3</th>
<th>Peak 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1.0</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Location</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

5. Conclusions

The grating spectrometer was used for dispersion and the spectrum dispersed was detected by linear CCD array, which realized the spectrum real-time measurement. In order to meet the requirement of the spectrum resolution of 2 nm, the grating of 300 lp/mm and the linear CCD array of TCD1251UD were chosen, the proper slit width of 0.14mm was determined; The spectral calibration function was established by the least square polynomial fitting, error of the wavelength calibrated was 0.037 nm; The spectral noise produced by the ambient light and the dark-current of CCD array were effectively suppressed by subtracting the signal in the dark state from the signal in the adjacent bright state to the same pixel; The random noise was processed by the wavelet threshold optimization algorithm, the details of the signal were perfectly reserved, maximum of the peak error and the peak location were 1.0 % and 0.3 % respectively. The correct measurement of the spectrum was achieved.

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References


