Random Noise Reduction with More Accurate Calibration for a Spectrometer Using a Two-Dimensional Array Detector

Chen ZHANG, Ming-hui LIU, Kai-yan ZANG, Wei-jie LU, Hai-bin ZHAO, Rong-jun ZHANG, Song-you WANG, Yu-xiang ZHENG and Liang-yao CHEN*

Opt. Sci. & Eng., Fudan University, Shanghai, China, 200433
*Corresponding author

Keywords: Spectrometer, Gratings, Image data, Noise-reduction.

Abstract. An efficient noise-reduction method with a more accurate wavelength calibration procedure is proposed for a spectrometer system to achieve a higher signal-to-noise ratio and spectral resolution. By using a two-dimensional (2D) array detector with an integrated grating composed of 10 sub-gratings, the system has a merit of high data acquisition speed to satisfy the condition in which in-situ spectral data analysis is critically required. The noise level has been effectively reduced down to approximately 25% of the previous level. The spectral curvature effect due to imperfection of the optical system is also analyzed and significantly reduced using the spectral calibration procedure to achieve higher resolution.

Introduction

In the modern information age, it is important to measure and analyze spectral data at a very fast speed with high spectral resolution and reliability, especially in situations in which in-situ spectral data analysis is critical and significantly required [1-6]. The mechanical component used to scan the wavelength in a spectrometer has physical limitations to affect the system reliability and data acquisition speed in a broad spectral range. To overcome this limitation, an advanced spectrometer without any mechanical moving parts had recently been studied, in which a 2D array detector is uniquely used to directly measure the spectral lines on the focal plane of the detector [4].

For the spectrometer using linear array detectors, only one wavelength signal per pixel can be measured each time. To reduce the random noise of the spectrum to a level of $1/k$ times, then $m (m = k^2)$ times of measurements are required to increase the data acquisition time by at least $k^2$ times with lower data measurement efficiency in applications. Manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper.

In the practical design and application of the spectrometer, the spectral resolution will be lower than that shown under the ideal conditions due to imperfection of the optical system of the spectrometer [7-10], arising from the off-axis distortion of the reflection mirror in the optical path to make the image of the input slit be curved on the focal plane, referring to the phenomenon called the spectral curvature ("smile") effect to reduce both the spectral resolution and the accuracy of the spectral measurement to precisely determine the line shape of the spectra in the data analysis procedure [10-12].

By making continuous effort to study and solve the problem, in this work, a new and more accurate spectral calibration method was proposed to reduce the "smile" effect for the spectral-folded spectrometer using the 2D array detector. Using this method, we were practically able to reduce the average spectral resolution from 0.26 nm to 0.23 nm, an improvement of 0.031 nm (about half of the pixel resolution, 0.069 nm per pixel) or by approximately 12 percent for the system, and to make the advanced spectral-folded spectrometer with high resolution get more significant and wider applications in the future.

Configuration of the Spectrometer

The spectrometer used in this work has the optical configuration in which the spectral image is
densely 10-folded to achieve approximately 0.069 nm spectral resolution and a 2-ms data acquisition
time in the 1450 nm to 1650 nm wavelength region [4]. The 10 sub-gratings were set at slightly
different angles to diffract light in 10 sub-spectral regions. The integrated grating causes the spectral
lines in each sub-spectral region to be imaged onto the focal plane of the 2D InGaAs array detector.
The integrated grating has a size of about 100x100 mm$^2$. Using an ultra-wideband source
(UWS-1000) [13], the image of 10 sub-spectral regions on the focal plane is presented in figure 1.
The 2D array detector has an effective photon sensing area of 9.6x7.68mm$^2$(320x256 pixels).

**Noise Reduction in Optical Measurement**

For the spectrometer studied in this work, there are three main approaches to reduce the system noise
by obtaining $N$ data of the spectral signal at each wavelength:

1. Performing $m=N$ spectral measurements using the linear array detectors, which can only obtain
   the signal per pixel each time, resulting in a decrease in the data acquisition efficiency and speed.

2. Using 2D array detectors, each horizontal line containing 320 signal pixels can be considered as
   an independent spectral analyzer. There are $n=N=25$ lines of pixels in each sub-wavelength region
   on the focal plane of the 2D array detector. By only taking one measurement of data in minimum time,
   $N$ sets of spectral lines can be efficiently obtained.

3. Combining these two methods (here, $N=m \times n$), the accuracy of data measurement in the
   experiment can be improved:

   \[ S_f = \frac{S_i}{\sqrt{mn}}. \]  

   where $S_i$ is the standard sampling deviation[14,15].

![](Image)

Figure 1. The signal images of 10 sub-spectral regions are clearly visible on the focal plane of the 2D InGaAs infrared
array detector in the 1450-1650 nm wavelength range.

**Results and Discussion**

**Method to Reduce the Noise Error**

After subtracting the dark background noise from the spectrum, the signals accompanied by the random noise will remain in the spectrum as shown in figure 2. A very weak spectral line at the 1560
nm wavelength position is initially buried in the random noise and cannot be clearly resolved, as
shown in figure 2(a). The signal intensity of the spectral line is enhanced by suppressing the random
noise with the data sampling numbers of $m = 9$ and $n = 9$ ($N = n \times m = 81$), as shown in figure 2(b).
According to (1), the standard error is reduced by 9 times. It is clear that the effectiveness of the
procedure reduces the random noise and improves the measurement quality of the data in the
experiment.

In comparison with the method using the 2D array detector, there are $n$ spectral lines in each
sub-spectral region to be measured and analyzed by only taking $m = 1$ scan of the spectra at high speed.
The value of the standard sampling deviation $S_f$ is reduced to approximately 26% of its initial value for
the number of $n=17$ in this work by scanning the spectral data only once ($m=1$). This result is the advantage of the spectral data acquisition using the 2D array detector with higher efficiency to achieve a higher signal-to-noise ratio, especially in the situation in which the in-situ measurement and monitoring of the spectral data with high speed are critically required.

![Figure 2](a) The random noise with the intensity level comparable to that of the weak spectral line at the 1560 nm wavelength. (b) After data reduction by taking the sampling number $m=9$ and $n=9$, the signal-to-noise ratio is greatly improved to enhance the weak spectral line at the same wavelength position.

**Reduction of “Smile” Effect and Calibration**

The optical system of the spectrometer is not perfect, and some distortion of the slit image on the focal plane will be induced, called the “smile” effect [12], implying that the input slit at each wavelength will not be a perfect vertical line measured on the focal plane of the 2D array detector. As observed in the “smile” effect of the spectrometer studied in this work in figure 3, the image of the input slit on the focal plane of the 2D array detector is slightly tilted and not perfectly aligned along the vertical direction in the sub-spectral region.

Therefore, due to the “smile” effect, the signal intensity measured at the pixel position along the vertical line direction will not be equal to that at the same wavelength position. The error will occur to reduce the resolution of the spectral line using the method in which the light intensity is simply averaged along the vertical direction, as observed in figure 4.

Because the entire 1450-1650 nm wavelength range of the spectrometer is divided into 10 sub-regions with a narrow spectral window of only approximately 20 nm, the “smile” effect on each wavelength pixel position will exhibit a similar feature in the same sub-spectral region but may exhibit a slightly different feature in other sub-spectral regions.

At the starting step of data reduction, the quasi-monochromatic light signal at the pixel position [16]. The slit image of the wavelength appears in the sub-spectral region to be measured and is analyzed for its peak intensity with respect to the pixel position $x$. The procedure is performed for each row of the image data on the focal plane of the 2D detector. The pixel position $x_j$ for each wavelength at the $j$th row can be precisely determined. Afterwards, a step of wavelength $\Delta \lambda$ is added to perform the same calibration for the new wavelength until all the wavelengths in the sub-spectral region are calibrated. Using the polynomial interpolation method, the wavelength in all the rows
along the vertical direction can be precisely calibrated. The same calibration procedure is performed for the other sub-spectral regions to achieve a precise calibration for all the wavelength data points in the entire spectral region of the spectrometer using the 2D array detector.

![Image](attachment:figure3.png)

Figure 3. The “smile” effect of the quasi-monochromatic slit image that is slightly distorted on the focal plane of the 2D array detector. (a) The images of the input slit at each wavelength in sequence: 1530 nm, 1535 nm, 1540 nm, 1545 nm, 1550 nm, 1555 nm, 1560 nm, 1565 nm, and 1570 nm. (b) The single slit image at the 1560 nm wavelength is amplified to clearly illustrate the “smile” effect.

Therefore, the calibration procedure presented in this work can correct the “smile” effect to achieve a better signal-to-noise ratio (SNR) for the data. To improve the experimental SNR, the quasi-monochromatic spectral line at the 1460 nm wavelength produced by the MLS-8100 laser source is inputted into the spectrometer [16]. The line shape of the laser beam was measured and analyzed using the old and new calibration procedures, and the results are compared in figure 5. Using the new calibration procedure, the signal intensity of the spectral line increases from 500 to 700 with an enhancement of approximately 40%, and the line shape narrows by approximately 0.04 nm. In other words, the new calibration method will provide better spectral data quality with a higher SNR and spectral resolution for the spectrometer using the 2D array detector.

![Image](attachment:figure4.png)

Figure 4. Schematic demonstration of the “smile” effect, which reduces the resolution of the spectral line. (a) In a perfect optical system without the “smile” effect, the spectral lines along the vertical direction are all centered at the same wavelength position, resulting in a narrow and sharp spectral line shape using the data calibration procedure. (b) Due to the “smile” effect, the spectral lines along the vertical direction are not centered at the same wavelength position, resulting in a broadened line shape with relatively poor resolution using the conventional data calibration procedure.
The test of the new calibration method was also performed for other wavelengths, and the results are presented in figure 6. The average spectral resolution, referring to the full-width-at-half-maximum (FWHM) of the spectral line, is reduced from 0.26 nm to 0.23 nm, an improvement of 0.031 nm (about half of the pixel resolution, 0.069 nm per pixel) or by approximately 12 percent for the system. These results further confirm the merit of the new calibration method for the spectrometer using the 2D array detector.

**Conclusion**

By using the merit of the spectrometer using the 2D array detector, new data reduction and calibration procedures were studied and provided a better SNR with a higher data acquisition speed and efficiency. The spectrometer has an integrated grating structure composed of 10 sub-gratings that divide the spectrum into 10 sub-spectral regions. There are approximately 320x25 pixels in each sub-spectral region. A comparison between the data obtained using 1D and 2D array detectors is presented to illustrate that both a high data acquisition speed and better SNR can be achieved using the 2D array detector, which is especially suitable for in-situ measurement and monitoring of spectral data in applications. Using the new calibration method described in this work, the noise level has been effectively reduced to approximately 25% of the previous level. The "smile" effect caused by imperfections of the optical system was also analyzed and significantly reduced to achieve a higher resolution with better SRN. The methods and results presented in this work will be useful for applications of the advanced spectrometer in which the 2D array detector is the key optoelectronics device used to measure spectral data with high efficiency.
Acknowledgment

This work was supported by the National Natural Science Foundation of China under project contract number #61427815.

References


