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Correction and analysis of noise in Hadamard transform spectrometer with digital micro-mirror device and double sub-gratings

Xiangqian Quan [a,b], Hua Liu [a,*], Zhenwu Lu [a], Xiangzi Chen [a,b], Xiaoduo Wang [a,b], Jialin Xu [a], Qun Gao [a]

[a] *Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*

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ABSTRACT

In order to correct spectra anomaly in Hadamard transform (HT) spectrometer with digital micro-mirror device (DMD) and double sub-gratings (DSG) which was proposed by our research team, the analysis of noise is carried out from two aspects, one noise is the intensity noise caused by the instability of light source, detector, substance concentration, electrical system, *etc*. The other noise is the spectral response noise caused by the diffraction efficiency of DMD and DSG. Consequently, the effects of these noises on Hadamard transform encoding matrix equation are determined and the decoding matrix equations are derived. As a result, the method of inserting testing masks is proposed to correct the intensity noise and the method of correcting spectra by spectral response function is presented to correct the spectral response noise. The simulation results show that the Pearson correlation coefficient (PCC) between detected spectra and original spectra is enhanced gradually from 0.9108 to 0.9997 and the experimental results also demonstrate those two methods are valid, concise and significant.

1. Introduction

In recent years, as its several potential advantages over a common spectrometer such as lower cost, higher resolution, higher light capture efficiency and wider spectral range have been demonstrated by Kevin J. Kearney et al. [1,2], the Hadamard transform (HT) spectrometer based on digital micro-mirror device (DMD) has been widely investigated [3–5]. An affordable spectrometer based on DMD with high performance was developed by Bjarke Rose et al. [6]. SUN et al. [7–9] developed an engineering prototype of Hadamard transform spectral imager based on DMD. E. S. Voropai also designed a multi-object spectrometer with micro-mirror array [10].

In our research team, by using the programmable characteristic of DMD, Wang et al. designed a HT spectrometer with DMD and double sub-gratings (DSG) [11], which the spectral range was increased and the spectral resolution was enhanced. However, the noise giving rise to anomaly in spectra need to be analyzed as well. One noise was the intensity noise caused by the instability of light source, detector, substance concentration, electrical system, *etc*. The other noise was the spectral response noise caused by the diffraction efficiency of DMD and DSG. For the intensity noise, Eric Pruett et al. treated the intensity noise as additive noise in column scan DMD based spectrometer [12] and subtracted it on basis of inserting full “off” state static masks. However, since the detected energy is larger in DMD-based HT spectrometer, the method will not eliminate the deviation completely. For spectral response noise, Kenneth D. et al. have carried a lot of experiments to measure the diffraction of DMD based spectrometer and tried to mitigate the noise by designing optical structure [13,14]. But they have not analyzed the effect of DMD diffraction on code equation theoretically. What is more, the spectral response noise is more complex in spectrometer with DMD and DSG and can not be eliminated by designing optical structure. J. Xu et al. used to propose a new algorithm to correct the anomaly in spectra caused by optical defects [15], but these two noises haven not been taken into account. Those methods are heuristic for spectra correction in our spectrometer. In this paper, after analyzing the cause of intensity noise, the intensity noise is determined to be multiplicative and time-related. By analyzing the effects of intensity noise on HT encoding matrix equation, the de-noising decoding matrix equation is deduced and the method of inserting full “on” state testing masks is proposed accordingly to mitigate the intensity noise. Then after analyzing the diffractions of DMD and MSG, the spectral response noise is determined to be multiplicative and wavelength-related. By analyzing the effects of spectral response on HT encoding matrix equation, the de-noising decoding matrix equation

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[*] Correspondence to: Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, No. 88,Yingkou Road, Changchun 130033 China. Fax: +86 43186176295

E-mail address: quanxiangqian137@126.com (X. Quan).

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is deduced and the method of correcting spectra on basis of spectral response function is proposed as well. The simulation results show that the Pearson correlation coefficient (PCC) between detected spectra and original spectra is enhanced gradually from 0.9108 to 0.9997. By establishing apparatus of DMD based spectrometer, these two methods are determined to be of correctness, conciseness and significance.

2. Theory of HT spectrometer with DMD and DSG

The schematic of HT spectrometer with DMD and DSG is shown as Fig. 1 [11]. Polychromatic light from fiber is collimated by the collimating lens. The collimated light is split by DSG and focused onto the DMD by imaging lens. Consequently, after encoded by DMD according to HT encoding matrix , the different spectrum components concentrate onto the single detector by converging lens. Eventually, the spectra are decoded and displayed by the computer. The Hadamard transform encoding process can be described as Eq. (1):

$$\mathbf{I} = \mathbf{H} \times \mathbf{E} \tag{1}$$

where **E** is the original spectra matrix, **H** is the HT encoding matrix which instructs encoding masks, and **I** is the detected intensity matrix.

The HT decoding matrix can be described as Eq. (2):

$$\mathbf{E} = \mathbf{H}^{-1} \times \mathbf{I} \tag{2}$$

where $\mathbf{H}^{-1}$ is the inverse of **H**. **E** can be acquired by Eq. (2).

In our design of HT spectrometer with DMD and DSG, the collimated light is split by DSG with incident angles of 12.6° and 6.7° and focused onto the DMD by imaging lens with incident angle of 24°, the spectral range is from 0.8 μm to 2.0 μm, the numerical aperture (NA) of fiber is 0.22, the diameter of fiber is 100 μm, the DMD consists of 1024 × 768 micro mirrors with pixel size of 13.68 μm × 13.68 μm and tilt angle of ± 12° mounted on a 14.68 μm × 14.68 μm pitch, the dimension of grating is 12.8 mm × 6.4 mm with a groove density of 300 lines/mm and blazing wavelengths of 1.0 μm and 1.6 μm, and the spectrum resolution on DMD is superior to 5.5 nm. The simulation result of the HT spectrometer with DMD and DSG is shown in Fig. 2. There are two columns of spectrum on DMD. Due to the imperfection of optical design, processing and alignment, the spectrum diffracted by DSG can not be spliced perfectly and the same spectrum may appear on the DMD repeatedly. For this reason, two Hadamard transform matrixes are established for each column of spectrum.

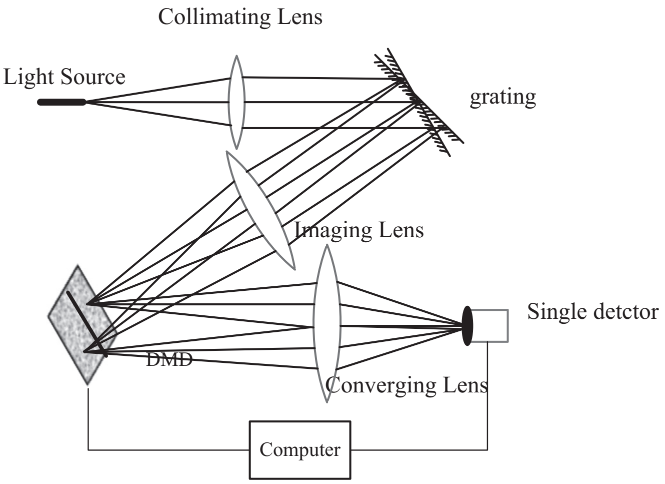

Fig. 1. Schematic of spectrometer with DMD and DSG.

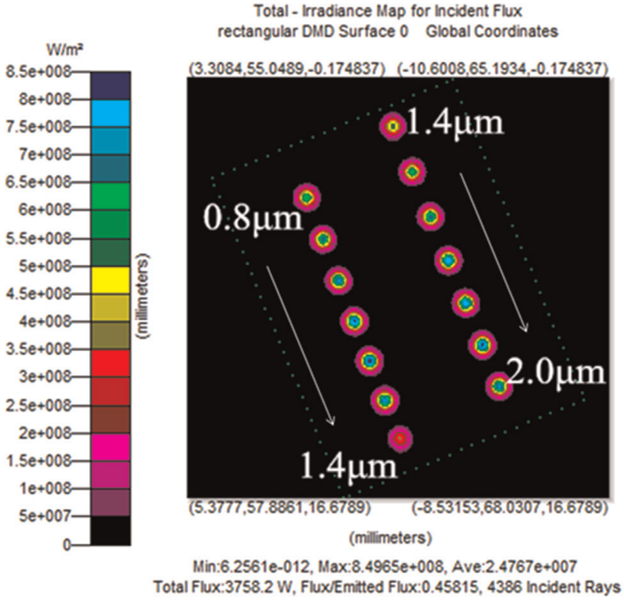

Fig. 2. Irradiance map for incident flux on DMD surface.

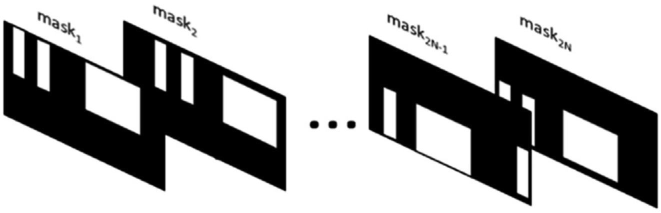

Fig. 3. The Hadamard transform pattern of HT spectrometer with DMD and DSG.

Then the ideal spectra can be derived by decoding separately.

The encoding pattern is shown as Fig. 3. When one column of spectrum is detected, the other column spectrum is neglected, and then two sets of encoding and decoding matrix equations are introduced .

3. Analysis and correction of noise

3.1. The analysis and correction of intensity noise caused by the instability of light source, detector, substance concentration, electrical system, etc.

Due to the instability of light source, detector, substance concentration, and electrical system, *etc.* In spectrometer, the detected intensity signal will be zoomed in or out and the computed spectra will be distorted. In the circumstance of the intensity of noise is in accordance with sine wave with amplitude of 0.01 and frequency of 0.002/mask, the effects of intensity noise on spectra are shown in Fig. 4(a), where 127 order Hadamard transform is carried out. The computed spectra are distorted accordingly which is shown in Fig. 4(b). It can be derived that the spectra may be distorted largely by weak noise.

In order to quantify the effects of intensity noise. The Pearson correlation coefficient (PCC) is introduced which is described as Eq. (3):

$$r_{xy} = \frac{\sum\left(X - \overline{X}\right)\left(Y - \overline{Y}\right)}{\sqrt{\sum\left(X - \overline{X}\right)^2 \sum\left(Y - \overline{Y}\right)^2}} \tag{3}$$

where X and Y denote two discussed variables, respectively, $\overline{X}$