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SNR analysis and Hadamard mask modification of DMD Hadamard Transform Near-Infrared spectrometer

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ABSTRACT

The noise of Hadamard Transform (HT) Near Infrared (NIR) spectrometer includes not only the detector circuit noise but also the illumination noise. Hadamard Transform reduces the detector noise while increases the illumination noise. If the relative power intensity is large, the noise of Hadamard method will be greater than that of scanning method. This will lose the significance of Hadamard Transform. In this paper the SNRs of the Hadamard method and scanning method are analyzed. The condition of boosting SNR of spectrometer by Hadamard transform is given. When the condition is not matched, a Hadamard mask of variable height stripes is proposed which the SNR of Hadamard method can be improved. In this paper a HT NIR spectrometer based on 0.45-inch DMD is designed with the spectrum range from 1350 nm to 2500 nm. Several experiments are done with the designed spectrometer. It is shown that with the Hadamard mask of variable height stripes the average SNR is improved by a factor of 2.2 at the short wavelength band and by a factor of 2.8 on the long wavelength band, and the minimum SNR on the whole wavelength band is improved by a factor of 2.3.

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1. Introduction

The Near-Infrared (NIR) spectrometer has been applied in chemical analysis (molecule containing C–H, N–H, S–H or O–H bonds), food processing, pharmaceutical monitoring, textile and other industries, due to its fast, non-invasive and non-destructive detection [1]. Fourier Transform (FT) NIR spectrometer is widely used in chemical analysis for its high wavelength resolution and high SNR. Traditional grating spectrometer either consists of fixed grating and linear array detector or consists of scanning grating and single-element detector. Linear array detector is expensive and scanning grating is complicated in mechanical structure. Hadamard Transform (HT) NIR spectrometer consists of single-element detector and fixed grating. Its high SNR and affordable price make it alternative for FT NIR spectrometer in some industries [2]. Although the principle of HT optics reached a stage of maturity relatively in 1970 s [3], the development of the HT spectrometer kept going slowly for the restriction of suitable spatial light modulator. Since the invention of Digital Micro-mirror Array Device (DMD), the NIR HT spectrometer has been developed and applied for chemical analysis. D. XIANG designed a NIR HT spectrometer based on 0.7 XGA (1024 × 768) DMD and used it to measure the multivariate quantification of glucose and lactate in binary mixtures composed in an aqueous buffer solution [4]. B. Rose designed two different spectrometers utilizing DMD and made comparison with diode array based designs [5]. X.D. Wang designed a spectrum-folded HT NIR spectrometer to widen the spectral range of measurement and improve the spectral resolution [6]. X.Q. Quan analyzed the spectra anomaly in HT spectrometer and presented a correction approach [7]. He also designed a stray light suppressed and DMD based spectrometer with a compound parabolic concentrator [8]. All these HT spectrometer are based on a 0.7 in. DMD. In this kind of DMD the micro mirrors' tilt direction is perpendicular to the hinge-axis which is positioned diagonally relative to the overall array. In recent two years, TI developed 0.45 in. DMD which the micro mirrors are arranged in diamond orientation. This arrangement simplifies the optical design of the spectrometer and reduces the spectrometer volumes. Eric in TI developed the spectrometer based on 0.45 in. DMD, and obtained the absorption spectrum of Polycarbonate and Acrylic [9,10].

HT spectrometer boosts the Signal-to-Noise Ratio (SNR) according to specific encoding patterns. The H-matrix [3,11,12], the S-matrix [13] and the complementary S-matrix [14] boost the SNR by a factor of $\sqrt{n}$, $\frac{n+1}{2\sqrt{n}}$ and $\frac{\sqrt{n+1}}{2}$, respectively. The boost of SNR is valid only for additive random Gaussian instrument noise. However, there is multiplicative noise in the instrument and the nature of noise places an important role in the boost of SNR by HT

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technique [15,16]. The additive random Gaussian noise (detector noise) is reduced and the multiplicative noise (illumination noise) is enhanced.

This paper presents a HT NIR spectrometer based on 0.45 in. DMD. The effect of HT on noise is analyzed for two kinds of system noises. The condition of SNR enhancement in HT spectrometer is deduced. When the condition is not matched in the spectrometer, a height variable HT mask is proposed to boost the SNR over whole NIR band. Particularly, the SNR over the sideband is boosted considerably by the proposed approach.

2. Design of the spectrometer

As shown in Fig. 1 the optical system of HT NIR spectrometer consists of slit, two-element collimating lens, grating, three-element imaging lens, DMD, three-element converging lens and detector. In order to manage the heat of high powered lamp, the optical fiber is used to keep the light source away from the optical system. The light is dispersed by a grating (150 grooves/mm with a nominal blaze wavelength of 1870 nm). Light incident to the DMD (DLP4500NIR) plane is modulated and reflected, and then focused onto a detector (2-stage thermoelectrically cooled, InGaAs, 2 mm^2). The detector signal is received by circuit system and processed by computer.

The electrical circuit structure is shown in Fig. 2. The components include detector driver, data acquisition, DMD controller, DMD, temperature controller and CPU with communication component. The DMD is controlled by DLPC350 which communicates CPU with USB. The patterns loaded onto the DMD are from FLASH memory and are designed according to Hadamard matrix. The resolution of the AD converter is 24 bits.

Usually, the matrix of Hadamard spectrometer is either the S-matrix or the complementary S-matrix [14]. The order of the matrix, either S-matrix or complementary S-matrix, is 2^N-1. The maxim number of the patterns displayed on the DLP4500 is 120 in this Hadamard spectrometer. The number is limited because the patterns are loaded from FLASH. If the number exceeds 120, the second time of pattern loading will be required. The timer interval of the two loadings is 2 s at least. Here a 103 order matrix is constructed by Quadratic Residue Construction method [3].

The parameters of the designed HT NIR spectrometer are listed in Table 1.

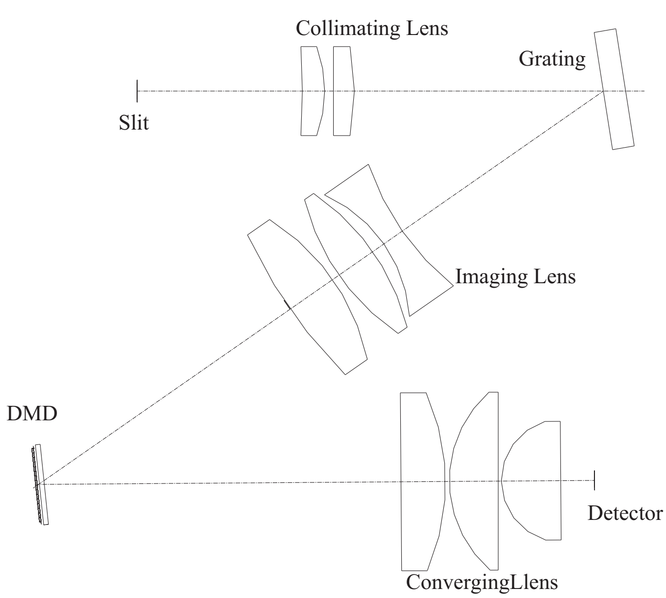

Fig. 1. Optical system of HT spectrometer.

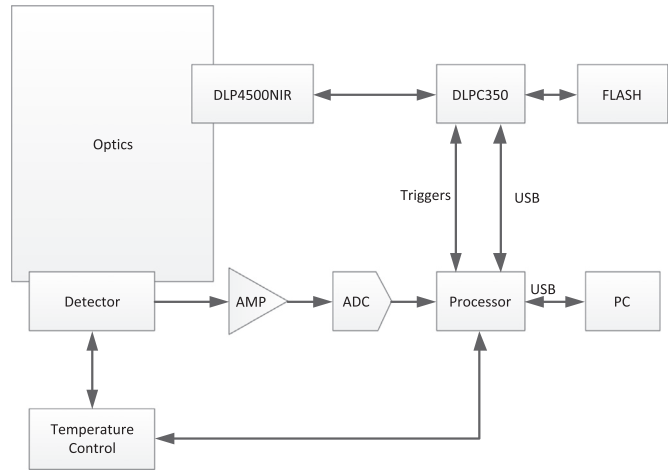

Fig. 2. Electrical circuit structure of HT spectrometer.

Table 1
parameters of the HT NIR spectrometer.

Spectrum Range	*1350–2500 nm*
Spectrum resolution	≤ 8 nm
Absorbency noise	$\leq 2\times10^{-4}$ AU
Absorbency range	0–3 AU
Wavelength reproducibility	≤ 0.2 nm
Sampling rate	1 S
Light source power	12 W
Size	150*150*120 mm^3

3. SNR analysis of HT spectrometer

The SNR of HT spectrometer depends on not only the noise from detector circuit but also the noise from light source [13–17]. In reference [14] A. Wuttig got the conclusion that Hadamard imaging spectrometer could achieve 50% of the maximum possible sensitivity if the noise was mainly from detector circuit. The nature of noise has an important influence on the signals generated by the HT [15,16]. The additive random Gaussian noise (detector noise) is reduced and the multiplicative noise (illumination noise) is enhanced by HT approach. Here the noise of the whole instrument is divided into two parts, the enhanced noise and the decreased noise. Only when the total noise is decreased will the Hadamard Transform make sense.

3.1. Condition of SNR boosting

Assume that the RMS of the illumination noise is σ, the RMS of the reconstructed signal noise after Hadamard transform will be $\sqrt{\frac{2n}{n+1}}\sigma$ [4]. The SNR actually deteriorates by an approximate factor. Assume that the RMS of the detector noise is Δ, the RMS of the reconstructed signal noise after Hadamard transform will be $\frac{2\sqrt{n}}{n+1}\Delta$ [17]. The two noises are combined together when calculating the total noise of the whole instrument. If the mask on the DMD is sequential stripes (scanning methodology), rather than multiplexing stripes (Hadamard matrix), the total noise will be remained. The HT methodology only works under the condition below:

$$\left(\frac{2\sqrt{n}}{n+1}\Delta\right)^2 + \left(\sqrt{\frac{2n}{n+1}}\sigma\right)^2 \le \Delta^2 + \sigma^2 \tag{1}$$

Where n is the order of Hadamard matrix, Δ is the detector circuit noise and σ is the illumination noise. Then we get the following equation:

$$\Delta \ge \sqrt{\frac{n+1}{n-1}}\sigma \tag{2}$$

When n is large enough, the detector noise is equal to or greater than the illumination noise.

3.2. Comparison of SNRs of the Hadamard methodology and the scanning methodology

The illumination noise of σ is proportional to the relative power intensity of the lamp. Assume that the relative power intensity of the lamp is D and the proportion coefficient is η. The SNR of Hadamard methodology is described as:

$$SNR_H = \frac{D}{\sqrt{\left(D\eta \times \sqrt{\frac{2n}{n+1}}\right)^2 + \left(\frac{2\sqrt{n}}{n+1}\Delta\right)^2}} \tag{3}$$

The SNR of scanning methodology is described as:

$$SNR_S = \frac{D}{\sqrt{(D\eta)^2 + (\Delta)^2}} \tag{4}$$

When $n=103$, $\eta=0.0002$ and $\Delta=16$, we get the SNR curves as shown in Fig. 3 where the abscissa is relative power intensity and the ordinate is SNR.

It can be seen from Fig. 3 that as the illumination power intensity increases from zero, the SNR increases for both of Hadamard and Scanning methodology. But the increasing speed is different. When the minimum SNR is set to be 2000, the required relative power intensity is above 7560 for Hadamard methodology and it is above 34,920 for scanning methodology. The former is much smaller than the latter. It can also be seen that when the power intensity increases to a certain level the SNR tends to be a steady value about 3500 for Hadamard methodology. This is because the illumination noise increases as the light source power increases. At certain level of the light source power, the illumination noise becomes larger than the detector noise. According to Eq. (2) the way of boosting SNR by Hadamard methodology is invalid in this case. The maximum SNR of the whole instrument becomes the SNR of the light source divided by the gain of the illumination noise ($\sqrt{2}$ approximately) according to Eq. (4).

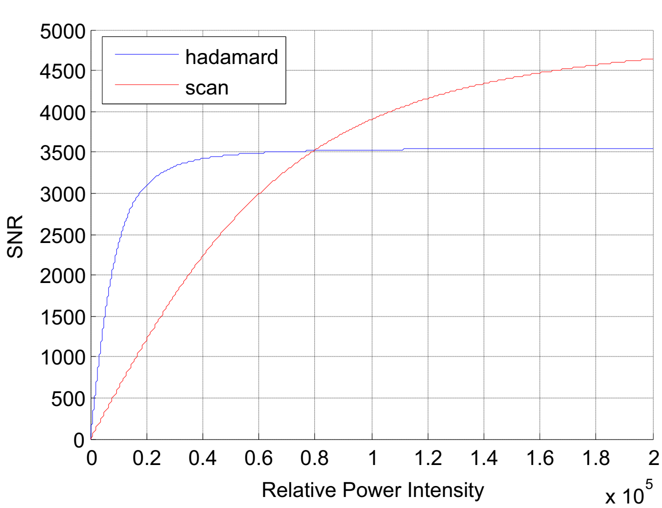

Fig. 3. SNRs of the two methodologies.

3.3. Hadamard mask of variable height stripes

It is easier to ensure HT spectrometer to work, if the intensity distribution of light source power over wavelength is flat. Suppose the required SNR is 2000. We can choose the relative power intensity to be 7560 for a light source with flat intensity distribution according to Fig. 3. Unfortunately, the relative power intensity is usually high at middle band of spectrum, and it is low at sidebands of spectrum. If we choose the relative power intensity at sidebands of spectrum to be 7560 for the required minimum SNR, the relative power intensity at middle band of spectrum will be much higher causing a large illumination noise. The condition of Eq. (2) may be not matched at middle band of spectrum, and Hadamard methodology loses its significance.

In this paper we propose an approach to overcome above difficulty by using a Hadamard mask of variable height stripes in DMD Hadamard spectrometer. Hadamard mask based on DMD is programmable, and the height of stripes of Hadamard mask at different wavelength can be controlled. In the process of Hadamard transform different apertures could be added to different wavelength. This will reduce the power intensity and so reduce the illumination noise at middle band of spectrum, and make it easier to match the condition of Eq. (2). With this type of Hadamard mask the SNR of the spectrometer at the sidebands of spectrum is boosted considerably as compared with either traditional Hadamard spectrometer or scanning spectrometer.

4. Experiments

The resolution of the DMD is 1140 × 912. There are 912 columns in the direction of the spectrum dispersion. 8 columns of micromirrors are grouped together as one stripe. There are 114 stripes totally. The order of the Hadamard matrix is 103. 8 stripes are redundant and are not involved in Hadamard mask coding. The light source should be turned on for 2 h before sampling. The steps of obtaining the noise data are as follow. Firstly, sample the spectrum for 16 times continuously. On each wavelength there will be 16 values of intensity. Secondly, take the mean square deviation of the values as the noise at the wavelength, and take the average of the 103 noises as the noise of the whole wavelength band.

4.1. The detector circuit noise

When the detector circuit noise was sampled the entrance of the optical fiber was blocked with a cap. The Hadamard method and the scanning method were carried out respectively. Fig. 4 shows the noise curves of the two methods. The abscissa is wavelength and the ordinate is relative power intensity. The red curve is the noise by Hadamard method and the blue curve is that by scanning method. The average noise by scanning method is 7.19 and that by Hadamard method is 1.39. Compared to scanning method Hadamard method reduces the noise by a factor of 5.17.

4.2. The noise of the spectrometer

The spectrum of the light source was measured by Hadamard method and scanning method respectively. The relative power intensity curves are plotted in Fig. 5. The abscissa is wavelength and the ordinate is relative power intensity. The red curve is the spectrum of the light source by Hadamard method and the blue

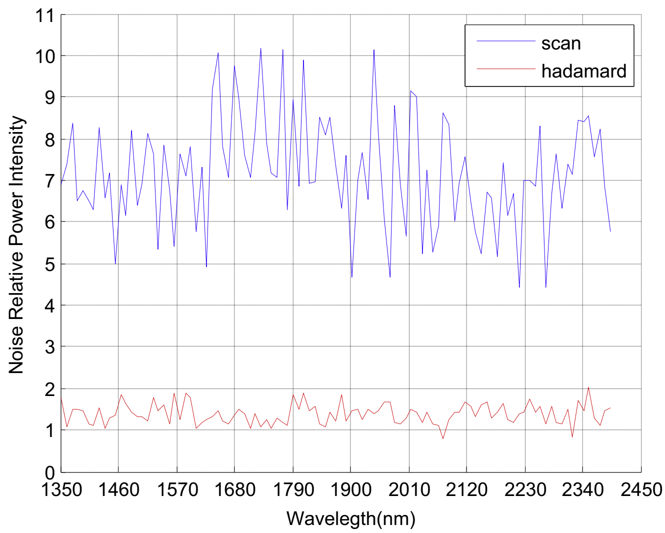

Fig. 4. Noise of Detector circuit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

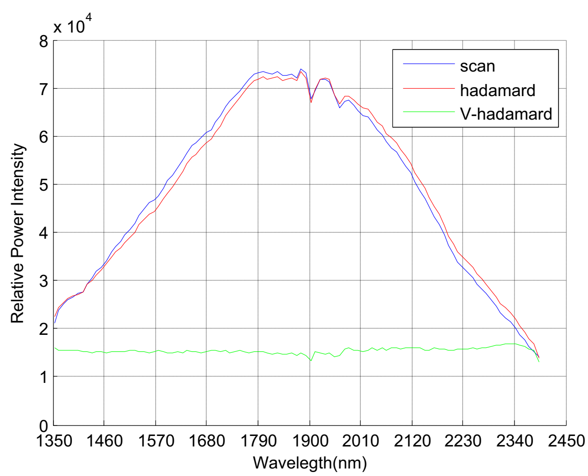

Fig. 5. Relative power intensity of the light source. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

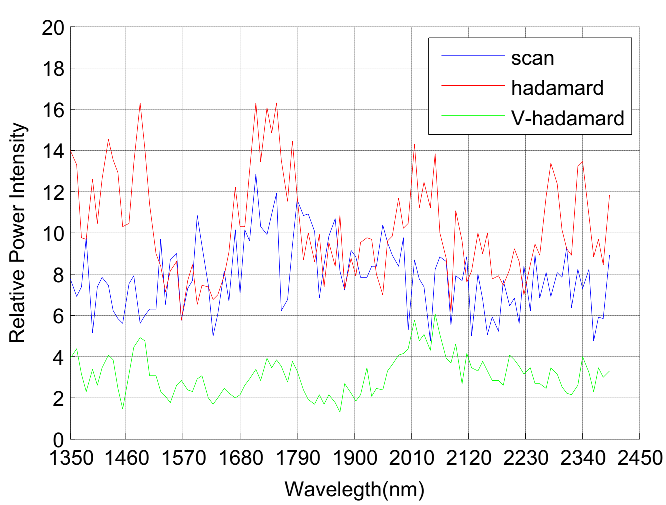

Fig. 6. Noise of the spectrometer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

curve is that by scanning method. The figure shows that the relative power intensity at the middle band of spectrum is higher than that at the sideband of spectrum.

The noise curves are shown in Fig. 6. The abscissa is wavelength and the ordinate is relative power intensity. The red curve is the noise by Hadamard method and the blue curve is that by scanning method. It can be seen that the noise by Hadamard method is larger than the noise by scanning method. The average noise of the whole wavelength is 7.84 for scanning method and it is 10.26 for Hadamard method. The SNR curves are plotted in Fig. 7. The abscissa is wavelength and the ordinate is SNR. The red curve is the SNR by Hadamard method and the blue curve is that by scanning method. It can be seen that the SNR by Hadamard method is less than that by scanning method. The reason is that the illumination noise at the middle band of wavelengths is large due to large power intensity which makes the condition of Eq. (2) unmatched.

Table 2 lists the average SNRs for short wavelength band, long wavelength band and whole wavelength band. We are more interested in the average SNRs at sidebands of spectrum. At short wavelength band the average SNR is 3919 by scanning method, and it is 2236 by Hadamard method. At long wavelength band the average SNRs are 2806 and 2083 by scanning method and by Hadamard method, respectively. These SNR values are quite low. Table 3 lists the minimum SNRs at short wavelength band, long wavelength band and whole wavelength band. The minimum SNR at whole wavelength band is 1609 by scanning method and it is 1168 by Hadamard method. Both of them are less than the required SNR of 2000 in our spectrometer.

4.3. Modification of the Hadamard Mask

In order to take advantage of Hadamard method to boost the SNR of the spectrometer when the condition of Eq. (2) of the light source is not satisfied, we adopt a new type of Hadamard mask which is with variable height stripes in DMD Hadamard spectrometer. Different apertures are added to different wavelength in the process of Hadamard transform. This will reduce the power

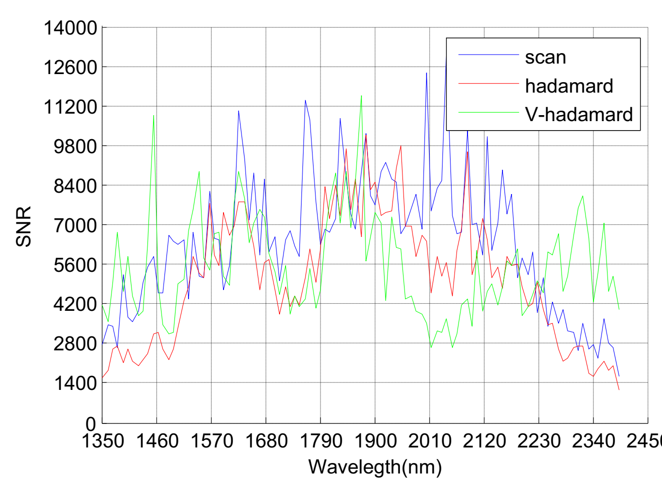

Fig. 7. SNR of the spectrometer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
The average SNR.

Wavelength range (nm)	*Scanning*	*Hadamard*	*V-Hadamard*
Short wave sideband (1350–1450)	3919	2236	4840
Long wave sideband (2290–2390)	2806	2083	5845
The whole band (1350–2390)	6368	5098	5529

Table 3
the minimum SNR.

Wavelength range (nm)	*Scanning*	*Hadamard*	*V-Hadamard*
Short wave sideband (1350–1450)	2673	1607	3588
Long wave sideband (2290–2390)	1609	1168	3977
The whole band (1350–2390)	1609	1168	2638

Fig. 8. Original Hadamard mask.

Fig. 9. Modified Hadamard mask.

intensity and the illumination noise, and make it easier to match the condition of Eq. (2). In details, the height of the stripes on the Hadamard mask is modified according to the relative power intensity of the light source. This is equivalent to adding different apertures to different wavelengths. The stripes of traditional Hadamard mask are shown in Fig. 8 and the variable height stripes of the proposed Hadamard mask are shown in Fig. 9.

In the procedure of the modification of the height of the stripes of Hadamard mask, the height of the minimum power intensity of Δ_{min} is taken as the highest height. Suppose the number of micro-mirrors of the highest stripe is H_{max}. The number of micro-mirrors of other stripe of H corresponding to the power intensity of Δ can be calculated by:

$$\frac{\Delta_{min}}{\Delta} = \frac{H}{H_{max}} \tag{5}$$

The relative power intensity curve acquired by variable-height-stripe Hadamard (V-Hadamard) method is shown as the green curve in Fig. 5, the noise curve is shown as the green curve in Fig. 6 and the SNR curve is shown as the green curve in Fig. 7. In Fig. 6, the average noise of the whole wavelength by V-Hadamard method is 3.06. It is reduced by a factor of 2.6 compared to scanning method and by a factor of 3.4 compared to traditional Hadamard method. Table 2 and Table 3 list the SNR values by V-Hadamard method. The average SNR on the short wavelength band is 4840 which is 2.2 times that of traditional Hadamard spectrometer and is 1.2 times that of scanning spectrometer. The average SNR on the long wavelength band is 5845 which is 2.8 times that of traditional Hadamard spectrometer and is 2.1 times that of scanning spectrometer. The minimum SNR on the short wavelength band is 3588 which is 2.2 times that of traditional Hadamard spectrometer and is 1.3 times that of scanning spectrometer. The minimum SNR on the long wavelength band is 3977 which is 3.4 times that of traditional Hadamard spectrometer and is 2.5 times that of scanning spectrometer. Particularly, the minimum SNR on the whole wavelength band is 2638 which is 2.3 times that of traditional Hadamard spectrometer and is 1.6 times that of scanning spectrometer.

5. Conclusions

In this paper a HT NIR spectrometer based on 0.45 in. DMD is designed. The spectrum range is from 1350 nm to 2500 nm. The resolution of DMD is 1140 × 912, and a 103-order Hadamard Matrix is used. The whole noise of the instrument is analyzed which includes not only the detector circuit noise but also the illumination noise. Hadamard method reduces detector circuit noise but increases illumination noise. Only when the detector noise is equal to or greater than the illumination noise by a factor of $\sqrt{\frac{n+1}{n-1}}$ will the Hadamard approach work. If this condition is not satisfied, a Hadamard mask of variable height stripes is proposed and constructed. Several experiments are done with the designed spectrometer. It is shown that when the illumination noise is large the traditional Hadamard method cannot increase the SNR of the spectrometer. With the modified Hadamard mask the average SNR of the spectrometer can be improved by a factor of 2.2 on the short wavelength band and by a factor of 2.8 on the long wavelength band. The minimum SNR on the whole wavelength band can be improved by a factor of 2.3.

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