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Design of a spectrum-folded Hadamard transform spectrometer in near-infrared band

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ABSTRACT

A spectrum-folded Hadamard Transform spectrometer in near-infrared band has been proposed and designed to widen the spectral range of measurement as well as to improve the spectral resolution. The full spectral region of 800 nm to 2000 nm is divided into two bands of 800 nm to 1400 nm and 1400 nm to 2000 nm and dispersed by two sub-gratings. The optimal incident angles of 12.6° and 6.7° respectively for two sub-gratings are chosen to achieve the highest diffraction efficiency. The results show that the spectral resolution of the system is better than 6 nm. The stray light from sub-gratings and DMD are suppressed to minimize the effect on the measurement results.

1. Introduction

Hadamard Transform near-infrared spectrometer based on DMD (digital micro-mirror devices) has no movable part, so the attractive performance of high speed, high resolution, high signal-to-noise ratio and strong adaptability to the environment can be achieved [1–4]. This kind of spectrometer has been widely used in agricultural products, petrochemical products, environmental monitoring and other fields.

The major supplier of DMD technology is Texas Instruments at present [5], and the DMD devices they provided are expensive and with fixed sizes, such as 800 × 600, 1024 × 768, 1280 × 720, and 1920 × 1080 pixels. Conventional Hadamard Transform spectrometers (HTS) with DMD contain one single planar grating and one DMD [6,7]. It leads to a mutual exclusion of wide spectral range and high resolution of currently available portable HTS. That is to say, when grating constant and the size of incident slit are determined, higher resolution will be sacrificed for expanding the working spectral range and vice versa. Moreover, in the two-dimensional DMD plane, the spectral length along the direction perpendicular to the spectral diffraction is much smaller than the width of DMD. As a result, most of the micro-mirrors in DMD are not fully utilized.

Another problem is lower optical throughput of the system. When the spectral range is wide enough, the grating diffraction efficiency in the full spectral range will be low which reduces the light efficiency. As near-infrared spectrum signal is usually faint, it is essential to take the light efficiency into consideration throughout the design process.

To achieve the wide working spectral range and high resolution as well, a new type of design of the HTS containing two sub-gratings is proposed. The spectrum is two-folded on DMD to double the spectral range from 800 nm to 2000 nm while the resolution is maintained. Furthermore, the influence of the incident angle on the diffraction efficiency of different wavelengths is studied, and the optimal incident angles of the two sub-gratings are respectively 12.6° and 6.7°. The stray light produced by gratings and DMD is also studied and suppressed. Simulation results show that the spectral resolution is better than 6 nm, and the diameter of the light spot in the single detector is smaller than 5 mm.

2. Principle and method

In this spectrum-folded HTS, the working spectrum, λ_1 to λ_3, is divided into two bands with equal width, λ_1 to λ_2 and λ_2 to λ_3. And λ_{B1} and λ_{B2} are respectively the corresponding central wavelengths of the two sub-wavelength bands. The incident angles of λ_{B1} and λ_{B2} are α_1 and α_2, and the diffraction angles of λ_{B1} and λ_{B2} are β_1

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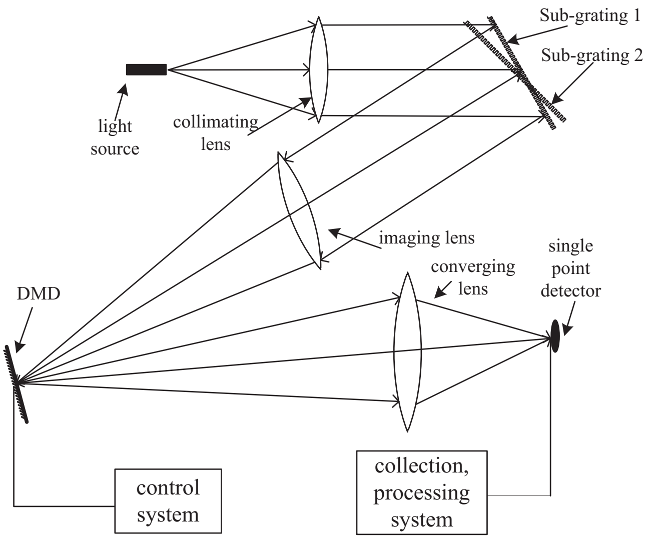

Fig. 1. Schematic layout of the spectrometer.

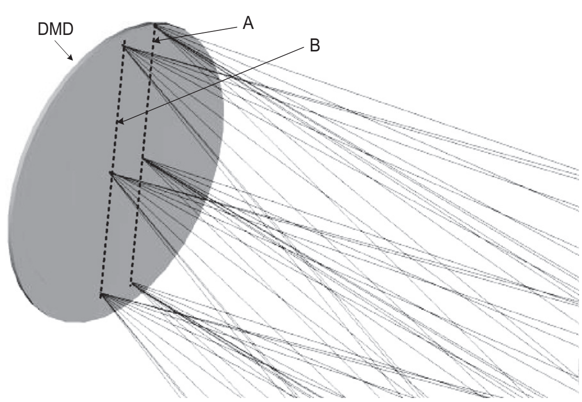

Fig. 2. Schematic of the spectra folded on DMD.

and β_2 [7]. According to the grating equation [8], the equal angle between the incident and diffraction light of each sub-wavelength band can be achieved by adjusting the incident angles α_1 and α_2, that is

$$\alpha_1+\beta_1=\alpha_2+\beta_2 \tag{1}$$

In this way, the diffraction light of the two sub-wavelength bands can be focused and aligned on the DMD.

Fig. 1 shows the configuration of the spectrometer. Instead of a single grating, two sub-gratings with the same groove spacing but different blaze wavelengths and incident angles are adopted in the design. Polychromatic light from fiber is transmitted on the spherical collimating lens. The collimated light is dispersed into two parts along the direction perpendicular to the incident plane with the same angular width, and then focused onto the DMD by imaging lens. The two spectral stripes A and B are aligned in parallel on DMD as shown in Fig. 2, and the DMD here is used as a mask to implement spectrum-encoding. Then the light comprising the modulated spectra are focused by converging lens onto the single detector [9,10]. Finally, the original spectrum signal information of the source light will be decoded by inverse Hadamard Transform.

3. Specific parameters

The numerical aperture (NA) of fiber is 0.22, and the diameter is 100 μm. A 0.7 XGA DMD chip with 13.68 μm micro-mirrors and a $\pm 12^{\circ}$ tilt angle is adopted. The wavelength width of band A is from 800 nm to 1400 nm and that of band B is from 1400 nm to 2000 nm. The two sub-gratings are designed to be plane reflection grating blazed at 1000 nm (corresponding to band A) and 1600 nm (corresponding to band B), with both a groove density of 300 lines/mm. The dimension of each sub-grating is 6.4 mm × 12.8 mm with grooves paralleling to the short side. The combination of two sub-gratings can be achieved by simply mechanical splicing.

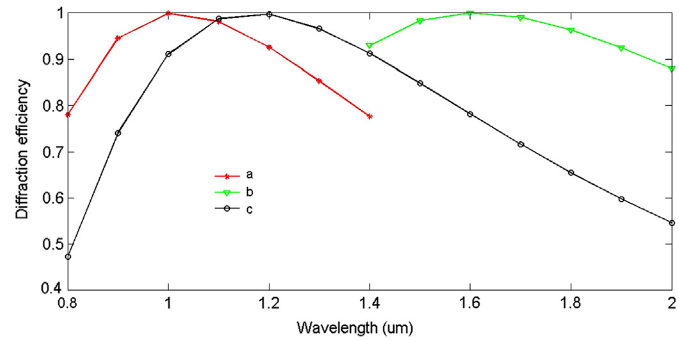

Fig. 3. Grating diffraction efficiency at different wavelengths: (a) band A, $\lambda_B=1000$ nm, $i=12.6^{\circ}$; (b) band B, $\lambda_B=1600$ nm, $i=6.7^{\circ}$; (c) bands A and B, $\lambda_B=1150$ nm, $i=12.6^{\circ}$ (i is the angle of incidence).

Optimal incident angles are chosen for the two sub-gratings to improve the grating diffraction efficiency. The grating diffraction efficiency's decline of band A is found when the incident angle is larger than 12.6°, so this angle will be the incident angle of sub-grating 1. The incident angle of sub-grating 2 is equal to 6.7° according to the grating equation and formula (1). Fig. 3 shows the grating diffraction efficiency at different wavelengths. The corresponding diffraction efficiency of band A and B can reach an excess of 75% and 87%, respectively, and the diffraction efficiency will be reduced to below 50% when a single grating is used for the full spectra band from 800 nm to 2000 nm. Obviously, light energy efficiency of the spectrometer can be substantially improved by using two sub-gratings blazing at different wavelengths.

The focal lengths of collimating lens and imaging lens are 30 mm and 50 mm, respectively. To eliminate spherical and chromatic aberration, the doublet spherical lens is combined with a single spherical lens. It is important to reduce the bending of spectral plane caused by field curvature and chromatic aberration because the reflective surface of DMD is a plane. Coma should be reduced as much as possible because it will cause the line profile unilateral diffusion on DMD and the resolution of the instrument will be reduced consequently. And the peak of the line profile will be displaced by coma to generate the false spectral lines [11]. The collimating lens and imaging lens are designed separately, and then optimized globally in the system.

4. Results and discussion

The optical system simulated by optical design software ZEMAX is shown as Fig. 4. Both the imaging lens and the converging lens are spherical, and the outer edges of the focusing lens are cropped to make sure that no element is blocked in the 3-D graphic. Fig. 5 shows the spectrum distribution on DMD, and it can be seen that the two sub-wavelength bands are parallel and end to end. The length of each spectral band is 12.6 mm, which is shorter than the DMD's length of 14 mm.

Theoretical resolution of the optical system can be derived by the following formula:

$$\delta\lambda=\frac{ad}{2mf_1}\cos i\cos\sigma, \tag{2}$$

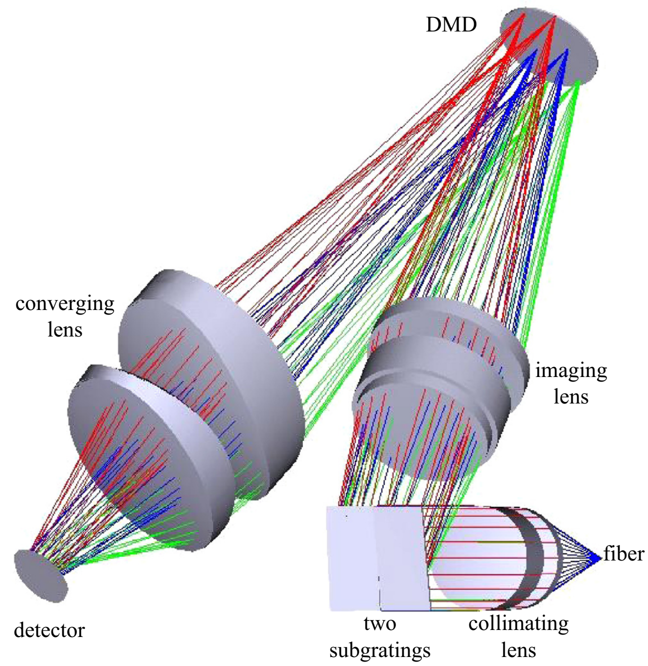

Fig. 4. Simulation result of spectrum-folded HTS.

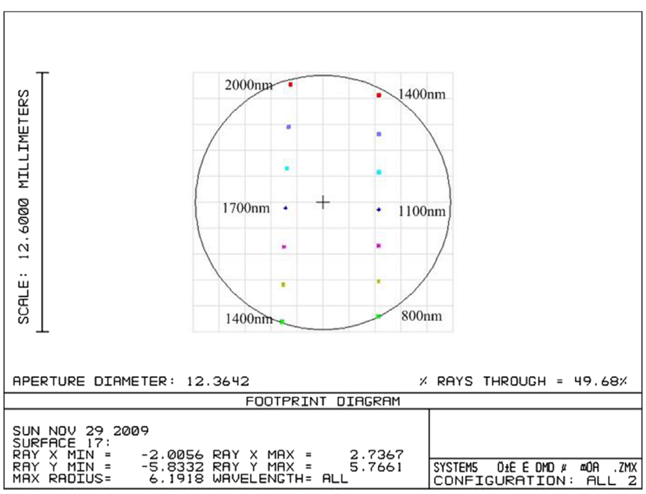

Fig. 5. Folded spectra on DMD.

where a is the diameter of fiber, d is the grating constant, f_1 is the focal length of collimating lens, and σ is the angle between the focal plane and the optical axis. Calculation results show that $\delta\lambda = 5.3$ nm at band A, and $\delta\lambda = 5.39$ nm at band B. According to the Rayleigh criterion, two diffraction spots can be distinguished when the minimum illumination between the two spots is 73.5% of the maximum illumination. In this way, the resolution of the simulated system is 5.5 nm (shown in Fig. 6), which is in good agreement with the theoretical values. The diffraction spots on the left side of Fig. 6 are the images of fiber on DMD, the curves on the right side are the corresponding illumination of the spots, and the vertical axes are the Y-coordinate of the images. The final image of the fiber on the single detector is an overlapped spot of different wavelengths and different field of view, as shown in Fig.7. The diameter of the overlapped spot is 4.8 mm, and a 5 mm (diameter) single detector can be cost-effective and small form factor compared with an array detector. The volume of the system is 74 mm × 62 mm × 43 mm.

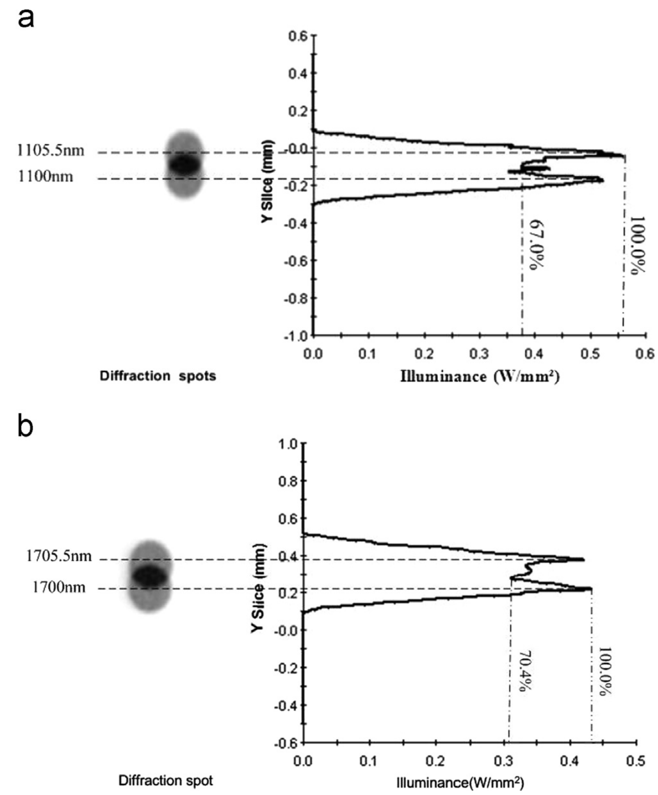

Fig. 6. The image of fiber and the illumination distribution on DMD.

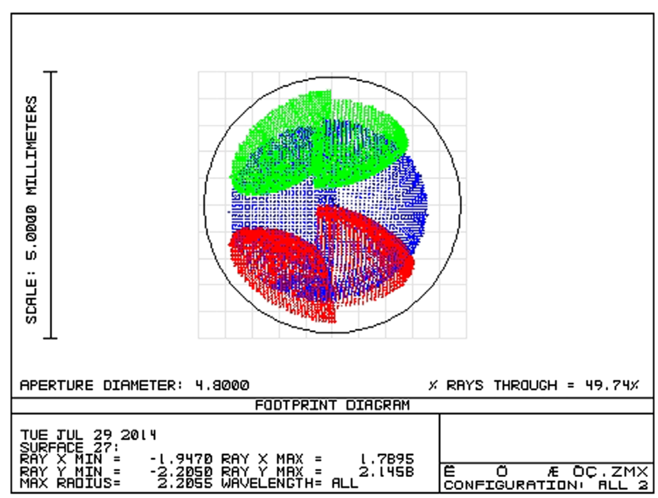

Fig. 7. The footprint of the final image on single detector.

Considering that the source light with broadband spectra will be incident onto both grating 1 and grating 2, the stray light produced by the two gratings should be suppressed. A band-pass filter with pass-band from 800 nm to 1400 nm is placed in front of grating 1 to block the wavelength from 1400 nm to 2000 nm. Another high-pass filter with the wavelength-cut edge at 1400 nm is placed in front of grating 2 to block the wavelength from 800 nm to 1400 nm, and the second order of the diffraction light is blocked simultaneously. Furthermore, the micro-mirror arrays on DMD can be seen as a two-dimensional orthogonal grating, which produces stray light as well. By calculating in Matlab, the normalized irradiance of order (0,0) in detector is 0.7858, while the highest irradiance of other diffractive orders is only 0.0455, as shown in Table 1. And the difference of incidence angles among different wavelengths on DMD is smaller than 0.3°, so the

Table 1
Irradiance of different diffractive order of DMD.

Order	(0,0)	(0,1)	(0,–1)	(1,0)	(– 1,0)
Intensity	0.7858	0.0455	0.0455	0.0214	0.0214

irradiance map of different wavelengths are almost the same as shown in Table 1. Generally, the faint diffractive light has almost no effect on the final measuring result. In some special situation, digital compensation is needed to make the measurement to be much more precise.

5. Conclusion

A spectrum-folded Hadamard Transform near-infrared spectrometer based on DMD is produced containing an integrated grating consisting of two sub-gratings. Spectra from 800 nm to 2000 nm wavelength are two-folded to achieve wide working wavelength range while the resolution is maintained. And the physical length of DMD is effectively extended to about 25.2 mm along the dispersion direction without any mechanical moving elements. 12.6°and 6.7° are chosen as the incident angles of two sub-grating to improve the diffraction efficiency. The results show that the system has a spectral resolution better than 6 nm. In terms of the advantages of this kind of HTS, its possible applications will include material inspection, material identification, and the monitoring of dynamic processes, such as epoxy-resin cure and in situ spectral monitoring of thin-film devices.

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References

[1] T. Hirschfeld, G. Wyntjes, Appl. Opt. 12 (1973) 2876.
[2] J.A. Decker, Appl. Opt. 10 (1971) 510.
[3] M. Hanf, R. Hahn, W. Dotzel, T. Gessner, Sensor Actuat. A—Phys 123 (2005) 476.
[4] B.L. Hu, L.B. Li, Z.H. Wang, Opt. Laser Technol. 44 (2012) 210.
[5] Benjamin Lee, Texas Instruments Application Report, ⟨http://www.ti.com/lit/an/dlpa008a/dlpa008a.pdf⟩, 2008.
[6] J. Liu, F.F. Chen, C.S. Liao, Q. Xu, L.B. Zeng, S.Q. Wu, Spectrosc. Spect. Anal. 31 (2011) 2874.
[7] M.H. Liu, S.X. Pan, Y.R. Chen, Y.F. Wu, Q.Y. Cai, P.H. Mao, Y.X. Zheng, L.Y. Chen, Opt. Exp. 17 (2009) 17.
[8] M. Born, E. Wolf, Principles of Optics, Cambridge, London, 2002.
[9] M. Kraft, A. Kenda, A. Frank, W. Scherf, A. Heberer, T. Sandner, H. Schenk, F. Zimmer, Anal. Bioanal. Chem. 386 (2006) 1259.
[10] A. Wuttig, R. Riesenberg, International Conference for Infrared Sensors and Systems, Erfurt, Germany, 2002, pp. 103–108.
[11] S.B. Utter, J.R.C. Lopez-Urrutia, Rev. Sci. Instrum. 73 (2002) 3737.