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Design and Experiment of Digital Mcro-mirror Spectrometer Optical System

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Abstract: A compact, low cost, high speed, non-destructive testing NIR (near infrared) spectrometer optical system is developed based on digital micro-mirror device (DMD). The application of DMD as wavelength scanning element in a traditional lens optical system enables the design of compact grating spectrometers capable of acquiring full spectra using a single detector element. Firstly, comparing with the traditional optical system, there is a new structure with a single detector. With the characteristics of DMD, the structure of the spectrometer system is proposed. After calculating the parameters of the optical path, ZEMAX optical software is used to simulate the system. Finally, the prototype is fabricated and calibrated. Designed for a wavelength range between 900 nm～1 500 nm, the spectrometer optical system features a spectral resolution of 19nm with the area of 70 mm×130 mm. If the width of slit is more than 200 μm, decreasing its width can increase the resolution of this prototype and the change of intensity is slow. Adding an aperture in the prototype can reduce the curved of the slit image in the spectrum. The system satisfies the demand of Near Infrared (NIR) micro spectrometer with a single detector.

Key words: Near infrared; Micro-mirror; Spectrometer; Single detector

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0 Introduction

According to Lambert law, Near Infrared (NIR) spectrum technology measures materials by the absorption of resonating frequency. On account of the advantages of non-destroy testing, fast and convenient, it has been widely applied in many domains, such as optics examination, biochemistry analysis, industry automatic detection, astronomy research and so on. With the development of optical measurement technology, stoichiometry technology, computer technology, NIR spectrometer based on optical micro-electro-mechanical system (MOEMS) becomes one of hot spots in the domain of instrument manufacture[1-2].

Presently, a fiber spectrometer and a concave grating spectrometer were developed by Chongqing University, and micro silicon multiplex spectrometer was manufactured by Changchun Institute of Optics[3-5]. And the Germany Fraunhofer institute has developed a micro-FT spectrometer and a micro-electro-mechanical scanning grating spectrometer, and America Polychromix Company pushed out a programmable DTS spectrometer[6-7]. In general, MOEMS has significant value on science and practical application. Therefore, on the basis of fundamental structure of micro spectrometer, a NIR spectrometer with the core component of DMD is proposed. DMD can be used to modulate light intensity and the spectrum can be tested by a single detector. Hence it can reduce the cost of the spectrometer. Furthermore, in respect of its programmable characteristic, DMD also can realize the function of hadamard masks and chopper so that the signal to noise ratio can be increased effectively.

A new structure of the NIR spectrometer with single detector is presented in this paper. Then, with the characteristic of DMD, an optical system

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is designed by the ZEMAX optical software. Finally, the prototype is fabricated and calibrated.

1 Parameter design of NIR spectrometer

The NIR spectrometer mainly consists with source, sample accessory, dispersed system and detection system and signal process system. This paper focus on the design of dispersed system. According to the demands of the spectrometer, the optical resolution and the pixel resolution can be calculated by the formulation bellow.

Optical resolution[8]

$$\delta\lambda = \frac{a_1 d}{m f_1}\cos i \cos \sigma \tag{1}$$

Pixel resolution

$$\delta\lambda' = \frac{dp\cos\varphi}{m f_2}\cos\sigma \tag{2}$$

As the result of the calculation, both parameters of the structure and the lens are show in Table 1 and Table 2.

Table 1 Parameter of the structure

Parameter	Value
Object distance/mm	75
Operating wavelength/nm	1 000～1 700
NA	0.6
The type of detector	PBS-050-E8
Slit/μm	400
The size of the pixel/μm	172.8
Image distance/mm	50
Chief wavelength/nm	1 300
Pixel resolution/nm	2.7
The photosensitive area of detector/mm	5×5
Grating/(lines • mm^{-1})	300

Table 2 Parameters of the lens

Surface type	Radius/mm	Glass
Collimating lens	38.76/infinity	Bk7
Grating	Infinity	Mirror
Second lens	25.84/infinity	Bk7
Third lens	15/-20; 15/-20	Bk7

2 Simulation of NIR spectrometer

On the basis of the parameters, ZEMAX software is employed to simulate the NIR spectrometer. 3D layout of the design and simulation is showed as Fig. 1[9]. In this figure, light which has already absorbed by the sample, go through a slit and incident into a collimating lens. It will then dispersed by a reflected flat surface grating. The second lens is used to focus the dispersed light onto the plan of DMD. DMD′s function is to select the light of different wavelengths. Finally, used the third lens to focus all the wavelengths and let them go into a single detector by time. After data processing, the spectrum can be measured.

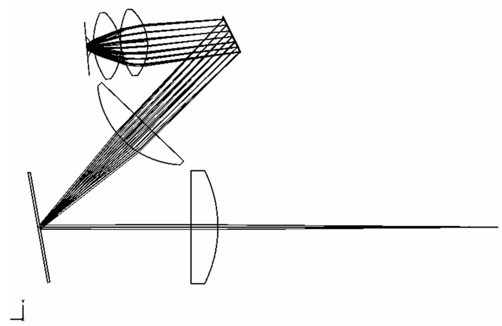
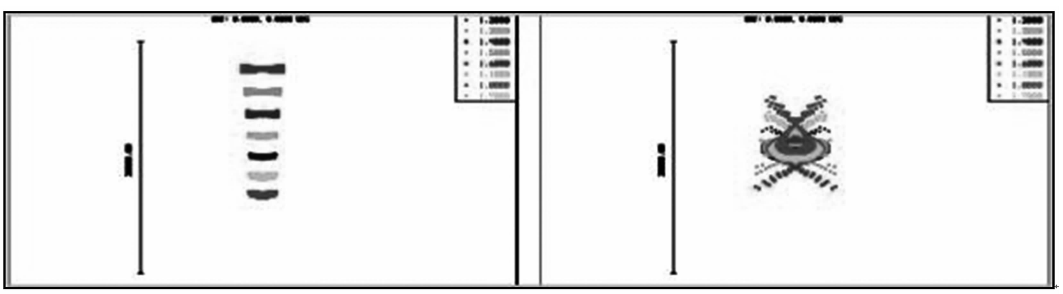


Fig. 1 3D layout of the simulation

What′s more, as the consequence of the simulation, the SPOT diagram is showed as Fig. 2 and Fig. 3. Fig. 2 is the spot diagram of the simulation with a barrier which height is 20 mm after the collimating lens. Owing to the height of the slit aperture which is 3 000 μm, the slit image is curved towards long wavelength showed as Fig. 2(a). And due to aberration, the third lens cannot focus the slit image into a single detector completely, showed as Fig. 2(b). The sensitive area of the detector is 5 mm×5 mm. when the height of barrier in front of the grating is 20 mm, the max diameter of the slit image on the plan of



(a) The plan of DMD (b) The plan of detector

Fig. 2 Spot diagram of the simulation with a barrier which height is 20 mm after the collimating lens

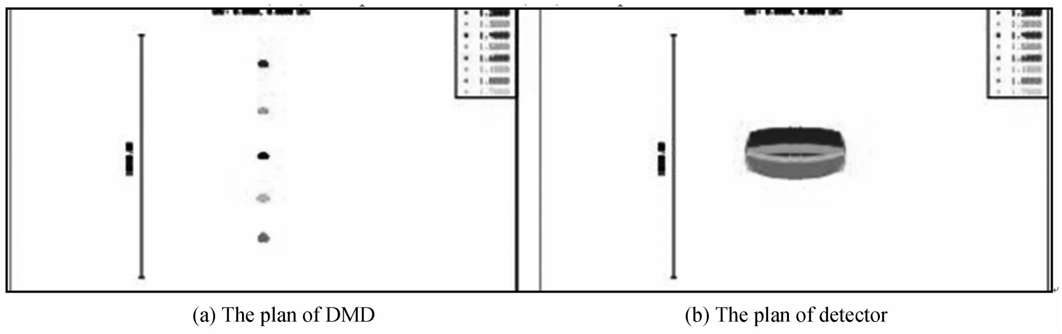


Fig. 3 Spot diagram of the simulation with a barrier which height is 5 mm after the collimating lens

the single detector is 5.566 84 mm>5mm. hence, the edge intensity of spectrum will be lost.

For the purpose of improving the image quality, the height of the barrier after the collimating lens is reduced to 5 mm. The spot diagram of the simulation is showed as Fig. 3. From Fig. 3(a), it is known by us that, to some extend, the curve of the slit image is decreased. And the max diameter of the slit image on the plan of the single detector is 1.831 68 mm<5 mm. The intensity of the spectrum can be tested by the detector thoroughly.

3 Experiment

The 3D layout of the prototype and the typical experimental set-up are showed in Fig. 4 and Fig. 5 Specific components include Bromine-tungsten lamp, D4100-DMD produced by texas instrument company , Lead sulfide single detector , blazed grating (d=1/300 mm, λ_b=1 250 nm).

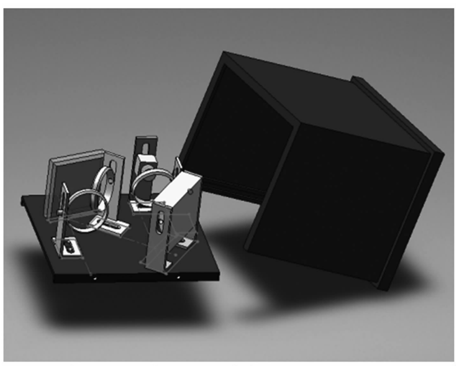


Fig. 4 3D layout of the prototype

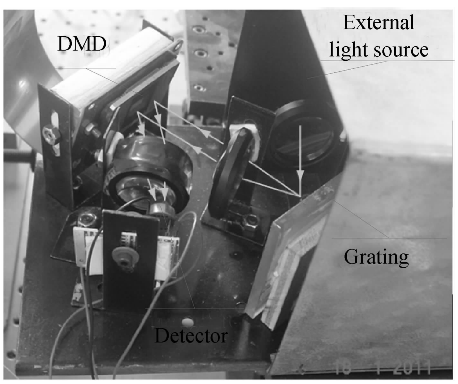


Fig. 5 The experiment set-up of the NIR spectrometer

The prototype of the NIR spectrometer was calibrated by the characteristic points of the interference band-pass filter. At first, the reference spectrum of the interference band-pass filter was tested by Shimadzu IRsolution 1.21 spectrometer whose resolution is 4 cm^{-1}. And then, to acquire the measured spectrum which was tested by the prototype, average and wavelet threshold de-noising were used. After calibration, the tested results are showed in Fig. 6. The solid line is the measured spectrum while the dotted line is the reference spectrum. From this figure it is clearly apparent that, the operation range of the spectrometer is 900~1 500 nm. And the resolution is 19 nm. There is excellent agreement between the reference spectra and the measured spectra, and Spectral accuracy relative error is 12.11%.

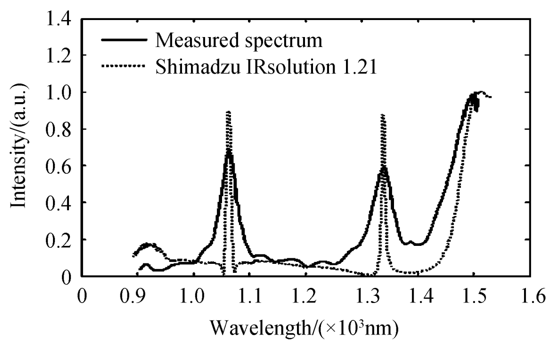


Fig. 6 Comparison of measured spectrum of a 1 063.8 interference band-pass filter with the referenced spectrum of Shimadzu IRsolution 1.21 spectrometer which resolution is 4 cm^{-1}

Additionally, with the change of the slit's width, the resolution and light intensity change regularly, show as Table 3. Both the resolution and light intensity are proportional to the width of the slit, which are agreed with the theoretical variation, and the slope of light intensity is smaller than the slope of resolution. So, changing the width of the slit can improve the resolution effectively and the lost of energy is small. But if the width of slit is less than 200 μm, decreasing the width can not increase the resolution and the signal-to-noise ratio decreases obviously because of diffraction and detector sensitivity.

Table 3 The relation between resolution and light intensity

Change the length of the slit			
Serial	1	2	3
Slit aperture/μm	380	650	910
Intensity/(a. u.)	1	1.175 6	1.325 3
Resolution/nm	19	33	51

Moreover, there is two ways to reduce the curve of slit image. One is designing a curved slit. The other is limiting the height of the parallel beam which incident into the grating. Actually, the cost of the slit with specific shape is high. So the second way is chose in this spectrometer.

An aperture is added in the prototype to limit the height in tangential plane. The measure result of the intensity is showed in Table 4. It's clear that decreasing the height of the aperture can improve the resolution, and energy is lost regularly.

Table 4 The relation between resolution and light intensity

Change the height of the aperture				
Serial	1	2	3	4
Slit aperture/μm	500	1 000	2 000	3 000
Intensity/(a. u.)	0.27	0.61	0.82	0.96
Resolution/nm	24	25	25	28

Finally, to determine the accuracy of the calibration, a 633 nm interference band-pass filter (FWHM 10 nm) is measured. After average and de-noising, the spectrum of second order is show as Fig. 7. The peak tested value is 1 263 nm which is 1266nm in theoretic and the accuracy of the wavelength is 3nm. As a result of that, the calibration is in accordance with actual value basically.

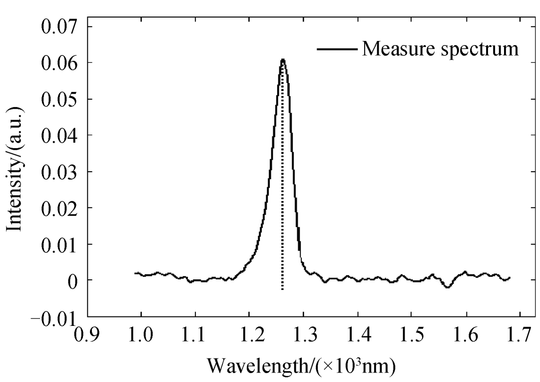


Fig. 7 The measured spectrum of a 633 nm (FWHM10 nm) interference band-pass filter which is the second order of diffracted light

4 Conclusion

According to the design requirements, a NIR spectrometer optical system based on DMD is developed. Then, with the characteristic of DMD, an optical system is designed, and optical components in the system are chosen. According to the demands of the spectrometer, parameters of the optical path are calculated and ZEMAX optical software is used to simulate the system. Besides, the prototype of the spectrometer is designed and the calibration is done. Finally, the typical parameters of the prototype are tested. The spectrometer optical system features a spectral resolution of 19 nm with a wavelength range between 900 nm~1500 nm; if the length of slit is more than 200 μm, the resolution of this prototype can be improved while decreasing the width of the slit. For the purpose of reduce the curving of the slit image in the spectrum, an aperture is used which can diminish tangential height of parallel light incoming into the grating. In the conclusion, the system satisfies the demand of NIR miniature spectrometer with a single detector.

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数字微镜近红外光谱仪光学系统设计与实验

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摘 要:针对传统光谱仪体积大、成本高、检测速度慢、需样品前处理等不足,提出了利用数字微镜面阵(DMD)实现光谱谱面分割分时选通的近红外光谱仪光学系统.首先,对比传统光路介绍单探测器微型光谱仪系统测量原理;然后结合DMD特性提出光路方案,根据几何光学原理进行初步光学元件选型和光路结构设计,利用ZEMAX光学软件对光路进行仿真,确定结构参数;最后,搭建实验平台,进行光路测试.实验结果表明:该系统光路尺寸为70 mm×130 mm,测量波段为(900~1 500 nm),分辨率可达19 nm;在能量损失较小的情况下,减小狭缝尺寸可提高光学分辨率,狭缝的极限尺寸为200 μm;减小狭缝子午面高度可减小谱面内弯曲现象.本系统基本满足近红外分光,实现单点探测器光谱测量的要求.

关键词:近红外;数字微镜;光谱仪;单探测器