

Principle and optimum analysis of small near-infrared spectrometers based on digital micromirror device

Liu Hongming^{1,3}, Liu Yujuan^{1*}, Song Ying¹, Zhong Zhicheng¹, Kong Lingsheng², Liu Huaibin²

(1. Key Laboratory of Geophysical Exploration Equipment, Ministry of Education, College of Instrumentation & Electrical Engineering, Jilin University, Changchun 130021, China;

2. Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130012, China;

3. Tonghua Normal University, Tonghua 134002, China)

Abstract: The DMD small near-infrared spectroscopy instrument is widely used in chemical composition analysis and quality inspection for its advantages of fast detection speed, high sensitivity, no damage detection, and miniaturization of portable instruments. However, as the premise of instrument design, optical optimization design of the whole spectral range is the hard work of the system. In this paper, the theoretical design method of the spectroscopic imaging system based on the small near-infrared spectrometer of DMD was studied. The method was designed by using the double-dispensing anti-aberration lens and combining the geometric aberration theory to optimize the design of a small DMD near-infrared spectrometer to reduce the aberration of the entire system. Then, the optical simulation software was used to align the direct imaging system for optical simulation. And ultimately achieve the design simulation requirements. Simulation results indicate that the whole size of the spectrometer is less than 150 mm×150 mm×150 mm, and the resolution is better than 15 nm in the range of 1 000-1 700 nm in the working band. Therefore, the proposed method can meet the design requirements and has broad application prospects in practical applications.

Key words: near-infrared spectroscopy instrument; DMD; principle and optimum analysis

CLC number: TH74 **Document code:** A **DOI:** 10.3788/IRLA20200427

基于 DMD 的小型近红外光谱仪原理及优化分析

刘宏明^{1,3}, 刘玉娟^{1*}, 宋莹¹, 仲志成¹, 孔令胜², 刘怀宾²

(1. 吉林大学仪器科学与电气工程学院地球信息探测仪器教育部重点实验室, 吉林 长春 130021;

2. 中国科学院长春光学精密机械与物理研究所, 吉林 长春 130021;

3. 通化师范学院, 吉林 通化 134002)

摘要: 数字微镜器件小型近红外光谱仪器具有检测速度快、灵敏度高、无损伤检测、仪器小型化等优点, 广泛应用于化学成分分析和质量检测。然而, 作为仪器设计的前提, 整个光谱范围的光学优化设计是系统的难点。文中研究了基于数字微镜器件小型近红外光谱仪的光谱成像系统的理论设计方法。该方法采用双配消像差透镜, 结合几何像差理论, 对小型数字微镜器件近红外光谱仪的设计进行了优化, 以降低整个系统的像差。然后, 利用光学仿真软件对准直接成像系统进行光学仿真。最终达到设计仿真要求。仿真结果表明, 该分光计的整体尺寸小于 150 mm×150 mm×150 mm, 在工作波段 1 000~1 700 nm 范围内, 其分辨率优于 15 nm。因此, 该方法能满足设计要求, 在实际应用中具有广阔的应用前景。

关键词: 近红外光谱仪器; 数字微镜器件; 原理与优化分析

收稿日期: 2020-12-05; 修订日期: 2021-01-07

基金项目: 国家自然科学基金(41974210, 61705221, 41504135); 吉林省创新能力建设项目(2019C035-1)

0 Introduction

Near-infrared spectroscopy refers to electromagnetic waves in the wavelength range of 780-2526 nm between visible light and medium-to-near-infrared light. It's produced by the absorption of the main frequency and frequency of molecular vibrations when a non-resonant vibrational molecule transitions from the ground state to a high energy level state^[1-10]. The analysis technology based on near-infrared spectroscopy is favored in chemical composition analysis, quality inspection and other fields due to its advantages of fast detection speed, high sensitivity, and no damage detection, etc. However, conventional near-infrared spectrometers are bulky, slow to sample, and costly for special environmental applications. With the urgent need for miniaturization and portability of instruments for special applications such as environmental testing and mineral exploration, small near-infrared spectroscopy equipment has become a research hotspot in recent years^[11-12]. This paper combines digital micromirror device (DMD) and grating near-infrared spectroscopy technology to study the small near-infrared spectrometer based on DMD. It mainly focuses on the simulation design method of the spectroscopic imaging system. It has broad application prospects in practical applications.

1 Basic principle of DMD-based spectrometer system

The DMD-based NIR spectrometer optical structure mainly includes a light source, a collimator lens, a grating, an imaging lens, a DMD, a focusing lens, a detector, a spectrum acquisition and processing system. The schematic structure is shown in Fig.1.

The light emitted from the light source passes

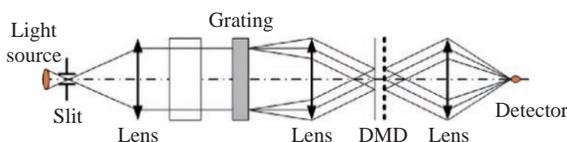


Fig.1 Schematic diagram of DMD-based spectrometer optical system

through the slit and then enters the collimator lens. The collimator lens collimates the light into a multi-color parallel light through the sample cell, and the light that carries the sample information is incident on the planar reflective grating for diffraction and dispersion into a spectral band. Then, the image of the slit is imaged on the surface of the DMD by the imaging lens according to the wavelength. At this time, the DMD has two states: the incident light is reflected into the converging lens when the state is +12°, and the incident light is reflected into the absorption cell when the state is -12°. All the light entering the converging lens is converged on the detector for receiving. The detector measures the light intensity of different wavelengths in time, and the spectrum diagram containing the sample information is obtained after data processing.

1.1 Spectral resolution

The entrance slit is an important factor of the spectrometer. The smaller the slit is, the higher the resolution of the system is. On the contrary, the lower the resolution, the smaller the slit is, the higher the energy is in the system. According to the Rayleigh criterion, the resolution can be expressed as:

$$R = \frac{\bar{\lambda}}{\Delta\lambda} = \frac{(\lambda_1 + \lambda_2)/2}{|\lambda_1 - \lambda_2|} \quad (1)$$

Assuming that the entrance slit width is a , spectral broadening $\Delta\lambda'$ can be expressed $\frac{a}{dl/d\lambda}$ according to the grating dispersion formula, where $dl/d\lambda$ is the liner dispersion of the grating^[13-14]. Moving λ_1 to the left $\Delta\lambda'/2$ made the spectrum resolvable, but the resolution of the spectrum is reduced and the resolution expression is:

$$R = \frac{\bar{\lambda}'}{\Delta\lambda'} = \frac{(\lambda_1' + \lambda_2)/2}{\lambda_2 - \lambda_1'} = \frac{4\bar{\lambda} + a/(dl/d\lambda)}{4\Delta\lambda + 2a/(dl/d\lambda)} \quad (2)$$

where $\lambda_1' = \lambda_1 + \Delta\lambda'/2$

1.2 Collimation and imaging objectives

The larger the focal length of the collimator lens is, the better the parallelism of the collimated light is. But when the system NA value is constant, increasing the focal length will increase the incident aperture, resulting

in an increase in system aberration and reducing the spectral resolution; In addition, it also increases the system's size and the cost of the instrument. The focal length of the collimator lens can be chosen to balance the needs of the above two aspects. After the incident light is split by the grating, it is incident on the DMD, and only the micromirror with the DMD is at 12° to reflect the incident light to the subsequent optical system. According to the principle of geometrical optics, without considering slit diffraction and aberration, the linear dispersion of the DMD surface can be expressed:

$$\frac{dl}{d\lambda} = \frac{d\theta}{d\lambda} \frac{f_2}{\cos\sigma} = \frac{m}{d\cos\theta} \frac{f_2}{\cos\sigma} \quad (3)$$

where σ is the angle between the central axis of the imaging lens and the focal plane normal. In the DMD operating state, σ is 12°. f_2 is the focal length of the imaging objective, the line dispersion rate is expressed as:

$$\frac{dl}{d\lambda} = \frac{L}{\Delta\lambda} \quad (4)$$

Using Eqs. (2), (3) and (4), the focal length of the imaging lens can be obtained:

$$f_2 = \frac{dl}{d\lambda} \times \frac{d\cos\theta}{m} \times \cos\sigma \quad (5)$$

1.3 Lens design

A lens is an optical element in which a transparent medium is interposed between two refractive surfaces. The refractive surface of the lens is mostly a spherical surface. According to the basic principles of geometric optics, the lens focal length is:

$$f' = -f = -\frac{f_1' f_2'}{\Delta} = \frac{nr_1 r_2}{(n-1)[n(r_2 - r_1) + (n-1)d]} \quad (6)$$

where f is the focal length of the object, f' is the image focal length, r_1 and r_2 are the radius of curvature of the two spherical surfaces of the lens, n is the refractive index of the lens, and d is the thickness of the lens^[15-16].

2 Theoretical design of small DMD near infrared spectrometer system

Spectrometer optical system structure needs to consider the working wavelength range, spectral

resolution, luminous flux, volume and its match with the detector and other factors^[17], the main performance parameters of the designed spectrometer are shown in Tab.1.

Tab.1 Main parameters of a DMD-based small NIR spectrometer

Parameter	Value
Wavelength range	1 000-1 700 nm
Spectral resolution	<15 nm
Size	<150 mm×150 mm×150 mm

2.1 Detector

In order to realize the miniaturization of the spectroscopy instrument and satisfy the requirement that multiple channels of data can be collected at one time, a receiver system with high sensitivity and low dark noise should be selected. The InGaAs detector manufactured by Pioneer Technology Inc. is selected as the spectral receiver which has a PDA that is sensitive to near-infrared light and meets the needs of the band of 1 000-1 700 nm. Its spectral response curve is shown in Fig.2.

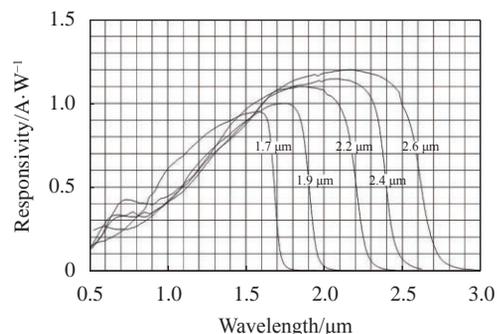


Fig.2 Corresponding curves of different bands of InGaAs single-point detector

2.2 Selection of DMD

The DMD-based small NIR spectrometer system uses a digital micromirror manufactured by Texas Instruments. The DLP4500NIR model has the advantages of fast switching speed and high reliability. It consists of 1 140×912 coated digital micromirrors, each with a size of 7.6 μm×7.6 μm and a diagonal dimension of 10.8 micrometer. Each micromirror can rotate ±12° around the axis of symmetry under the action of an electrostatic drive

circuit. Each angle corresponds to a different working state. Its working principle is shown in Fig.3. It keeps the direction of incident light unchanged. When the direction angle between incident light and the normal direction of the DMD surface is 24°, the light of the DMD surface is also emitting at 24° on the other side of the normal, rather than entering the optical system. When the incident light is +12° to the normal direction of the DMD, that is, the micromirror plane is rotated by 12°, the incident light is reflected by the DMD surface and enters the subsequent optical system; when the incident light and the DMD surface normal direction are 36°, the plane of the micromirror is rotated by -12°, and the reflected light and the incident light are emitted at 72°. Reflected light finally is absorbed by the light blocking plate.

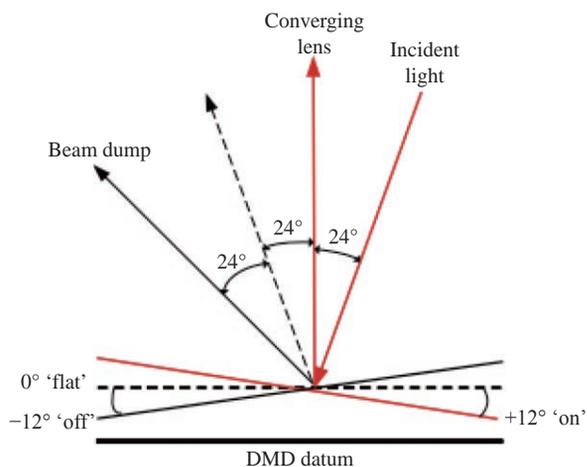


Fig.3 Digital micromirror working principle diagram

2.3 Grating design

The grating is a very important element in the spectrometer and can directly affect the resolution of the system. We select a planar reflective grating for spectral dispersion, from the grating equation:

$$d(\sin\theta \pm \sin i) = m\lambda \quad (7)$$

$(m = 0, \pm 1, \pm 2, \dots)$

where d is the grating constant, i and θ are the incident angle and the diffraction angle, respectively, and m is the diffraction order of the spectrum^[11]. Angular dispersion rate of grating can be expressed as:

$$\frac{d\theta}{d\lambda} = \frac{m}{d \cos\theta} \quad (8)$$

The dispersion rate of grating line is

$$\frac{dl}{d\lambda} = \frac{m}{d \cos\theta} f' \quad (9)$$

where f' represents the focal length of the imaging lens behind the grating. In this design, the line dispersion rate and the size of the DMD's micro-mirror determine the spectral resolution of the spectrometer. According to the theory of diffraction grating, $m=1$, $d=300$ l/mm, the blaze angle is 13.0°, and the grating diffraction efficiency curve of the aluminized film is shown in Fig.4.

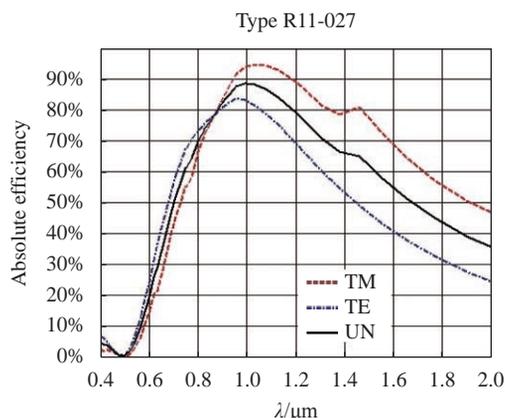


Fig.4 Diffraction efficiency curve

2.4 Optical system parameter design

According to the Eqs. (1)-(9), a theoretical calculation model is established by combining the parameters of the detector, the grating, and the DMD. The structural parameters of the optical system obtained using the model are shown in Tab.2.

Tab.2 Optical system design parameters

Parameter	Value
Working wavelength	1 000-1 700 nm
Slit length	1 mm
Slit width	50 μm
Collimating lens focal length	75 mm
Imaging lens focal length	45 mm
Raster line density	300 l/mm
DMD pixel size	7.6 $\mu\text{m} \times 7.6 \mu\text{m}$
DMD pixel number	1 140 \times 912 pixels
DMD tilt angle	$\pm 12^\circ$

3 Simulation and optimization

In this paper, the lens is designed as a plano-convex lens because the size of the object point and the aperture of the lens are small. The light source is an ideal point light source. The light path structure adopts a lens collimation light path. The collimating lens, the imaging lens, and the focus lens are designed using a double-glue to be used in a spectroscopic imaging light path system to reduce the influence of aberrations. The entire system is simulated. The resulting parameters of the system are shown in Fig.5, and the corresponding 3D structure system is shown in Fig.6.

Surf Type	Radius	Thickness	Glass	Semi-Diameter	Conic	
OBJ	Standard	Infinity	75.000	0.000	0.000	
1*	Standard	51.220	7.000	BR7	15.000 U	0.000
2*	Standard	-28.602	2.000	F2	15.000 U	0.000
3	Standard	-88.842	50.000		5.552	0.000
4#	Bifocals	Infinity	-25.000	MIRROR	15.000 U	0.000
5*	Standard	-65.149	-2.000	BR7	15.000 U	0.000
6*	Standard	-31.873	-7.000	F2	15.000 U	0.000
7*	Standard	48.805	-42.439		15.000 U	0.000
8*	DMD	Infinity	50.000	MIRROR	17.000 U	0.000
9*	Standard	Infinity	0.000		0.000 U	0.000
10*	Standard	25.000	14.000	BR7	17.000 U	0.000
11*	Standard	-10.000	4.000	F2	17.000 U	0.000
12*	Standard	-45.000	0.000		17.000 U	0.000
13*	Standard	25.000	14.000	BR7	17.000 U	0.000
14*	Standard	-10.000	4.000	F2	17.000 U	0.000
15*	Standard	-45.000	22.000		17.000 U	0.000
16*	Standard	Infinity	-		0.077	0.000

Fig.5 System parameter diagram

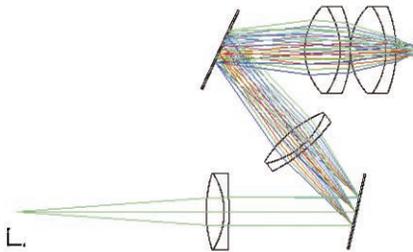
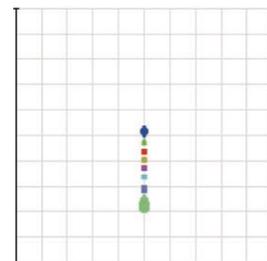


Fig.6 System optimization structure

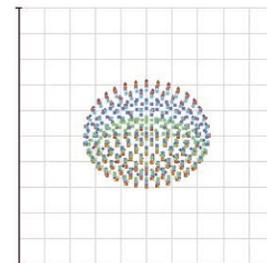
The proposed method does not consider the influence of the slit width on the optical resolution, the theoretical resolution of the optical system is calculated according to the parameters shown in Tab.2. The DMD is regarded as the theoretical focal plane of the system in this optical system. The distribution of the spectrum on the DMD is 8.57 mm, and the number of micromirrors covering the DMD in the direction of dispersion is 794. The dispersion rate of the grating line is $10.8 \mu\text{m}/\delta\lambda$, and the theoretical resolution of the available system is 0.88 nm. According to the Nyquist sampling theorem, the theoretical pixel resolution of the spectrometer is 1.763 nm. Considering the better image quality on the detector, the

aberrations and dimensions of the imaging image of the detector are optimized and limited. Fig.7(a) is the spot diagram of the point light source imaging after optimization. It can be seen from the figure that the optimized imaging quality is better, and the edge image aberration is smaller, the imaging quality is high, and there is no overlap between adjacent image points. If the spectral resolution of the imaging image at the detector is used to analyze the resolution of the spectrum, a higher resolution can also be achieved. However, in this optical system, the DMD replaces the position of the conventional detector for spectral reception, so the imaging quality on the DMD surface is mainly concerned. And the detector can simply converge all the monochromatic light into a single point detector. Therefore, the position of the detector is adjusted to achieve the most concentrated position of the light convergence, and the spot image of the spot imaging at the detector is shown in Fig.7(b).

In order to obtain the actual resolution of the simulation system, the wavelengths on the imaging at the DMD observed in the simulation are simulated according to (a) 1200 nm, 1210 nm, 1220 nm (b) 1300 nm, 1310 nm, 1320 nm (c) 1400 nm, 1410 nm, and 1420 nm, respectively. The images of the point map are shown in Fig.8.



(a) Imaging at the DMD



(b) Imaging at the DMD

Fig.7 Spot diagram of the system simulation

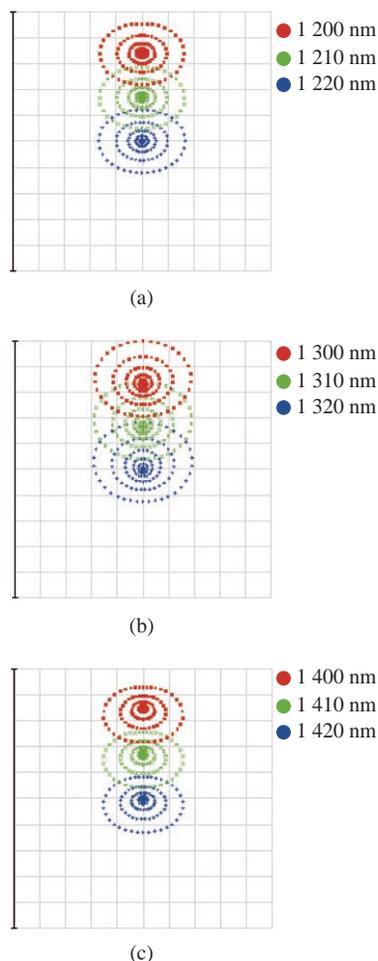


Fig.8 Spot diagram at different wavelengths during DMD imaging

According to the Rayleigh criterion, it can be obtained that any two spectral wavelengths separated by 10 nm on the DMD can be distinguished. It is better than the design target value and fully meets the actual resolution application requirements of the system.

4 Conclusion

The theoretical design method of the spectroscopic imaging system based on the DMD small NIR spectrometer is studied. A mathematical model for theoretical design is established. Theoretical parameters such as the resolution of the spectrometer and system aberrations are analyzed theoretically. The optical path system is calculated and designed using a lens collimation imaging scheme for the spectroscopic imaging system. The optical simulation is carried out using optical simulation software. Combining the geometric aberration theory, the double-

gluing anti-aberration lens is designed to optimize the design of a small DMD near-infrared spectrometer. Reducing the aberration effect of the entire system eventually reaches the design's simulation requirements. The results show that the whole size of the spectrometer is less than 150 mm×150 mm×150 mm, and the resolution is better than 10 nm in the range of 1 000-1 700 nm in the working band, which meets the design requirements.

References:

- [1] Xue Qingsheng, Wang Shurong, Li Futian. High precision linearity measurement instrument for ultraviolet photodetectors [J]. *Optics and Precision Engineering*, 2008, 35(7): 116-120. (in Chinese)
- [2] Wang Xin, Ding Xuezhuang, Yang Bo, et al. Optical system design and spectral characteristics calculation of prism spectrometer [J]. *Acta Optica Sinica*, 2010, 39(7): 1334-1339. (in Chinese)
- [3] Jin Zhao, Xiao Peng, Dai Jingmin. Development of a broadband infrared grating scan spectral radiometer [J]. *Infrared Technology*, 2005, 27(4): 343-346. (in Chinese)
- [4] Han Tao, Ni Weiming, Chen Liangyao. New pattern monochromator of multi-grating using two-dimensional color CCD array [J]. *Waves*, 2002, 21(S): 118-122. (in Chinese)
- [5] Gong Yan, Chen Bo. Optical design of an accurate focusing grazing incidence spherical grating monochromator [J]. *Acta Optica Sinica*, 2001, 21(5): 574-577. (in Chinese)
- [6] Wu Guoan. Design of Spectrometry[M]. Beijing: Science Press, 1978. (in Chinese)
- [7] Li Quanchen, Jiang Yuejuan. The Theory of Spectrometry[M]. Beijing: Publishing House of Beijing Institute of Technology, 1999. (in Chinese)
- [8] Chu Xiaoli, Tian Songbai, Xu Yupeng, et al. Study on rapid evaluation of crude oil by near infrared spectroscopy[J]. *Petroleum Processing and Petrochemicals*, 2012, 43(1): 89-93.
- [9] Herschel W. Investigation of the power of the prismatic colours to heat and illuminate objects [J]. *Philosophical Transactions of the Royal Society*, 1880, 90: 255-258.
- [10] O'Brien N A, Hulse C A, Friedrich D M. Miniature near-infrared (NIR)spectrometer engine for handheld applications[C]//SPIE, 2012, 8374(7): 3.
- [11] Lu Wanzhen. Near Infrared Spectrometer[M]. Beijing: Chemical

- Industry Press, 2010: 1-16.
- [12] Fan Shifu. Recent development of spectral technology and instruments[J]. *Modern Scientific Instruments*, 2006(5): 14-19.
- [13] Wang Xingquan, Feng Kecheng, Zhu Guoxian, et al. Study on the calculation formula of resolution and wavelength range of grating spectrometer [J]. *Acta Optica Sinica*, 2009, 38(5): 1167-1170. (in Chinese)
- [14] Xu Jialin, sun Qiang. Research on key technologies of Hadamard transform near infrared spectrometer based on DMD[D]. Beijing: Graduate School of Chinese Academy of Sciences, 2017. (in Chinese)
- [15] Guo Cheng. Design of low light level collimator with large field of view[D]: Changchun: Changchun University of Technology, 2009. (in Chinese)
- [16] Yu Daoyin. Fundamentals of Engineering Optics[M]. Beijing: China Machine Press, 2010. (in Chinese)
- [17] Tian Gaoyou, Chu Xiaoli, Yuan Hongfu, et al. Summary of main technical indexes and evaluation methods of near infrared spectrometer[J]. *Modern Scientific Instruments*, 2005(4): 17-20.



第一作者简介：刘宏明 (1981-)，男，吉林人，吉林大学博士研究生，2006 年于英国拉夫堡大学获得硕士学位，主要从事光谱分析技术研究。



通讯作者简介：刘玉娟 (1984-)，女，山东人，副教授，吉林大学大学博士生导师，2012 年于中国科学院大学获得工学博士学位，主要从事光谱仪器开发领域研究。