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集成线性渐变滤光片和 InGaAs 焦平面的微型光谱模组及其波长定标

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摘 要:提出一种集成线性渐变滤光片和 InGaAs 焦平面的微型近红外光谱模组.作为核心分光元件,线性渐变滤光片被紧密耦合在光敏芯片表面.相比于光栅分光方式,模组具有紧凑的光学结构和稳定的光学特性.对此光谱模组进行波长定标实验,并给出了标定准确性评价.实验结果表明,该光谱模组的波长范围为 900～1 700 nm,波长准确性优于 1.3 nm,光谱分辨率小于通道中心波长的 1.25%.基于此光谱模组的波长定标方法准确、可行,可以被用于微型近红外仪等在线光谱分析领域.

关键词:光谱学;InGaAs;焦平面;线性渐变滤光片;波长定标
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Integrated Linear Variable Filter/InGaAs Focal Plane Array Spectral Micro-module and Its Wavelength Calibration

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Abstract: An integrated spectral micro-module with a linear variable filter and an InGaAs focal plane array was proposed. As the core light dispersing element, the linear variable filter was coupled with an InGaAs detector array. Compared with the grating spectrometer, the micro-module has compact structure and stable optical properties. The wavelength calibration method and its accuracy were proposed and validated experimentally. The spectral range of the module is from about 900 nm to 1 700 nm. The calibration accuracy is better than 1.3 nm and the spectral resolution is no larger than 1.25% of peak wavelength. Experimental results demonstrate that the method of wavelength calibration is feasible and accurate. The spectral micro-module can be widely used in field or on-line applications.

Key words: Spectroscopic; InGaAs; Focal plane arrays; Linear variable filter; Calibration accuracy
OCIS Codes: 300.6340; 280.4788; 040.3060

0 Introduction

InGaAs detectors were widely applied in space remote sensing for its fast response and high sensitivity

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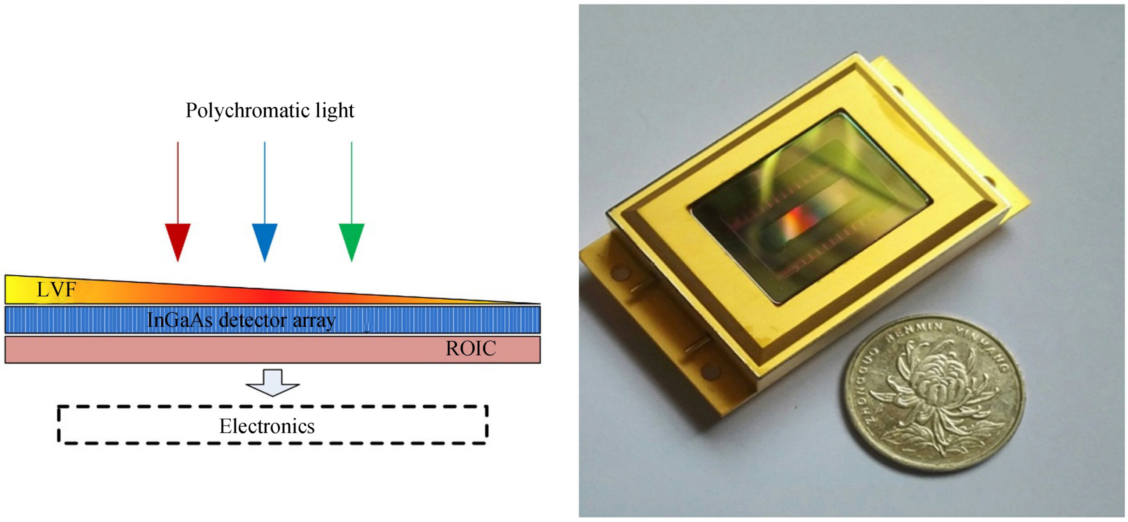
at near room temperature[1-2]. The $In_{0.53}Ga_{0.47}As$ material lattice is matched to InP substrate with cut-off wavelength at about 1.7 μm[3]. The cutoff wavelength of $In_{1-x}Ga_xAs$ material can be extended to 2.5 μm by adjusting the composition ratio of In component to 0.83[4]. In the Near-Infrared (NIR) spectral analysis applications, spectrometers with InGaAs detector were used in many fields such as food security, chemical industry and quality detection of agricultural products[5-6].

In recent years, the NIR spectroscopy industry is undergoing a major transformation of miniaturization and affordability[7]. A rising number of instruments are decreasing both in size and cost[8]. According to the number of pixels in the detector, these miniature handheld NIR spectrometers can be divided into different types. A single-element detector with a narrow-band filter forms the most sample and stable structure with the lowest cost, which can just be used to detect a specific wavelength feature of a substance. The grating scanning spectrometer can achieve a wider spectral range with a single-element detector. However it has an inferior performance for field applications in size, robustness and measurement time because of the existence of moving parts. Fixed-grating spectrometer with linear detector array has a short measurement time and good-enough spectral resolution normally around 1 nm[9], but the structure is still quite complex. Though the Czerny-Turner optical structure can reduce the size of instrument, it was still too heavy to be used in portable applications. The Linear Variable Filter (LVF) is a cuneiform and dielectric thin-film Fabry-Perot bandpass filter deposited using energetic processes[10]. As a result of the varying film thickness, the wavelength transmitted through the filter varies linearly in the direction of the wedge. The LVF spectrometer employs an LVF directly bonded to a linear InGaAs detector array, which results in an extremely compact and rugged structure with no moving parts. Compared to the grating spectrometers, this structure can reduce the complexity of optical train and increase the luminous flux at the same time. Such a spectral module has been proved to be a good choice for handheld or on-line applications with a moderate spectral resolution. The golf-ball-sized NIR spectrometer developed by JDSU is a successful case of LVF, which can be connected to computer by a USB cable[11]. In order to obtain reliable test results, spectral measurement devices need rigorous calibration. In ultraviolet band and visible light band, the standard light sources, such as mercury lamp, are widely used for wavelength calibration. However, high-performance monochromator and standard reference material are the better choice for the NIR waveband.

In this paper, we present an integrated NIR spectral micro-module with an LVF and a domestic InGaAs Focal Plane Array (FPA). The LVF is integrated with the FPA directly, which is mounted into a hermetic metallic package to form a solid structure. The wavelength calibration and performance evaluation of the module are also presented in detail. Compared to spectrometer, the spectral micro-module can be combined with different electronic design and has a better flexibility.

1 Methodology

The spectral micro-module is comprised by two components: a 900～1 700 nm LVF and adomestic 256-pixel uncooled InGaAs detector array integrated with low-noise Readout Integrated Circuit (ROIC), or so-called an FPA. Fig.1(a) illustrates the basic structure of the module. The interconnection of the ROIC and InGaAs detector array is achieved by bonding technology. In the early work, we have mastered the mature technology of the InGaAs FPAs. The average peak detectivity and the response non-uniformity of the FPAs are superior to 3×10^{12} cm·$Hz^{1/2}$/W and 5% at the room temperature[12]. The LVF is integrated directly to the InGaAs detector array, which makes each pixel of the spectral micro-module respond to a different center wavelength. The LVF is manufactured by Vortex Optical Coatings Limited in UK. The size is 15 mm long, 3.5 mm wide and 0.5 mm thick. In order to match the spectral range of our InGaAs detector array, a 900～1 700 nm type LVF is chosen. An image of the integrated NIR spectral micro-module is provided in Fig.1(b). Key attributes of the module are summarized in Table 1. As a core part of the portable devices used in field or on-line applications, the spectral micro-module is custom-designed to meet the low power-consumption and miniaturization requirement.



(a) Structure of the spectral micro-module (b) Image of integrated NIR spectral micro-module

Fig.1 Spectral micro-module integrated LVF and InGaAs FPA

Table 1 Key attributes of the spectral micro-module

Parameter	Specification
Spectral range	939～1 689 nm
Number of pixels	256(202 used in this module)
Pixel size /array pitch	50 μm×500 μm/50 μm
Dimensions	55 mm(L)×30 mm(W)×15 mm(H)
Weight	73 g
Power Requirement	<20 mA@5 V
Operating Temperature	－20～60 ℃

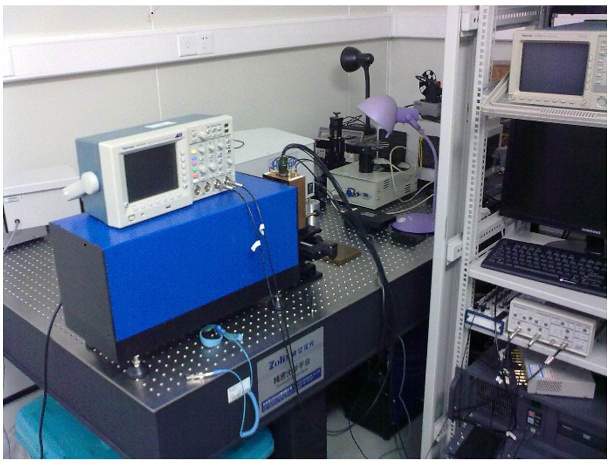


Fig.2 Universal electro-optic test bench for IR detectors

Calibration of the wavelength needs to be done before the application of this spectral micro-module. The calibration method mainly depends upon the relative spectral responses of all pixels, which are obtained by the universal electro-optic test bench for IR detectors[13]. In general, as shown in Fig. 2, the test bench incorporates the following equipment: the iHR550 monochromator (HORIBA, Japan) with a tungsten halogen lamp and a optical collimator; the DG2020A data generator (Tektronix, USA) used to generate the pulse sequences for spectral micro-module; the N6700B modular power system mainframe (Agilent Technologies , USA) used as power supply; the SR560 low-noise preamplifier (SRS, USA); an NI data acquisition card and a industrial computer with the data-processing software. The wavelength calibration process in this study can be achieved in three steps. Firstly, we test the relative spectral responses of all pixels from 900 nm to 1 700 nm with 1 nm stepping. The grating of iHR550 monochromator is set to 950 lines/mm. The entrance slit and exit slit are both set to 4 mm. The integration time of the spectral micro-module is determined by the pulse sequences of DG2020A, it is 3 ms in this paper. Secondly, for each pixel, we can get a curve with the wavelength as *X*-axis and the relative spectral response as *Y*-axis. In this way, we can get corresponding peak wavelength for every pixel. Finally, the NIR wavelength standard reference material SRM-2035a (NIST, USA) is used to verify the accuracy of wavelength calibration. SRM-2035a is a glass filter containing holmium oxide (Ho_2O_3), samarium oxide (Sm_2O_3), ytterbium oxide (Yb_2O_3), and neodymium oxide (Nd_2O_3)[14-15]. Due to the selective absorption of rare earth elements for different wavelengths of light, SRM-2035a has several standard absorption peaks in the NIR region.

2 Result and discussion

Fig.3 presents the relative spectral responses of the whole pixels ranging from about 900 nm to 1 700 nm. The Full Width at Half Maximum (FWHM) of each pixel distributes between 11 nm and 16 nm, which increases with the increase of peak wavelength by and large. All the FWHM are less than 1.25% of the peak wavelength, which is consistent with the specification of LVF. As shown in Fig.4, we use pixel 101 to 103 as example, λ_1, λ_2 and λ_3 were the peak wavelength of pixel 101 to 103. The peak wavelength of pixel 102 is 1 317.6 nm while the FWHM is 14 nm. The spectral interval between pixels ($\lambda_2-\lambda_1$ or $\lambda_3-\lambda_2$) is 3.7 nm and is less than the half of FWHM. So we take every pixel as a spectral channel and the value of FWHM should be the spectral resolution of channels. Thus, the wavelength calibration results of all pixels are obtained and shown in Fig.5. Because the selected LVF in this paper is a general type instead of custom-built, the match of the LVF and the InGaAs detector array is not so perfect. The effective size of LVF is a little short so that only 204 pixels are covered. The pixels from 205 to 256 are not used here. The

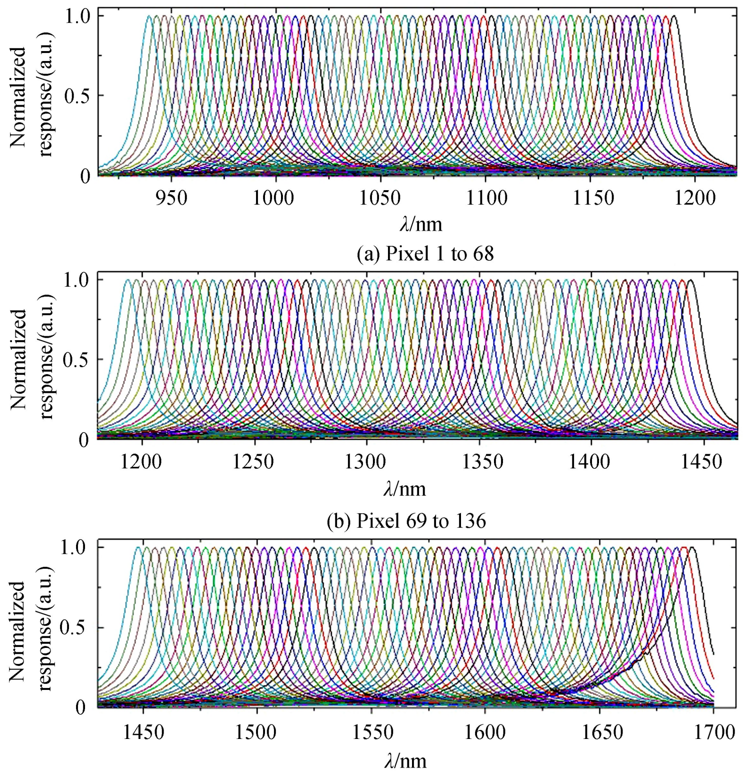


Fig.3　Relative spectral response of the whole pixels

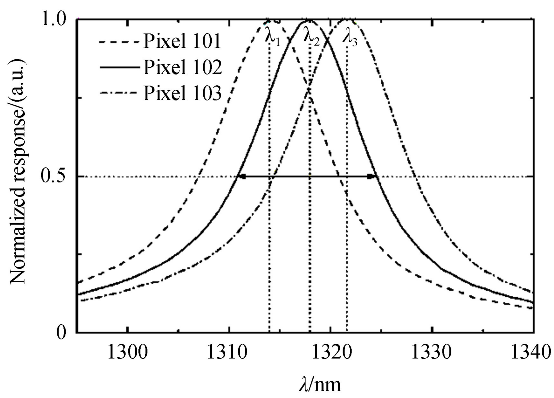


Fig.4　Relative spectral responses of pixel 101 to 103

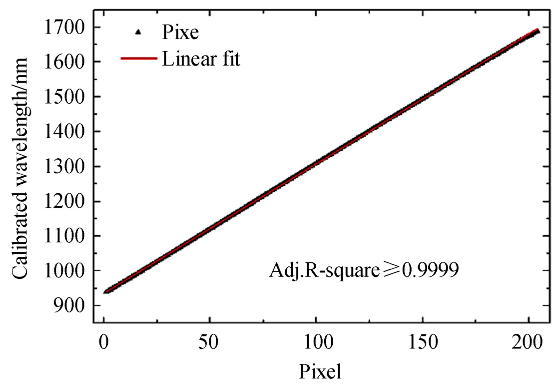


Fig.5　Calibration results of the whole pixels

wavelength intervals between two adjacent pixels have a good uniformity as desired and the average value is 3.72 nm. The wavelength distribution is strictly linear and the linear fit equation is shown as

$$y = 936.14 + 3.72x \tag{1}$$

where y is the peak wavelength and x shows the pixel number. It can be explained by two reasons. Firstly, the LVF is well-known for the stable and reliable optical properties, which owning to its wedge structure and mature manufacturing process. Secondly, the alignment technique in coupling process makes the LVF in an exact angle and position.

The verification of wavelength calibration is carried out by means of SRM-2035a. There are six standard absorption peaks in the wavelength range 900～1 700 nm[13-14]. The transmissivity of SRM-2035 a is measured by the calibrated spectral micro-module. We choose the deviation from standard wavelength as an index to show the accuracy of calibration. Fig. 6 shows the transmissivity spectra of SRM-2035a. The deviations are less than 1 nm as shown in Table 2, except for the wavelength peak No.5 (with 1.3 nm deviation). Considering the deviations caused by testing process , these small deviations will not affect the results in most applications of spectral analysis. In consequence, the verification result demonstrates that the calibration method is feasible and accurate.

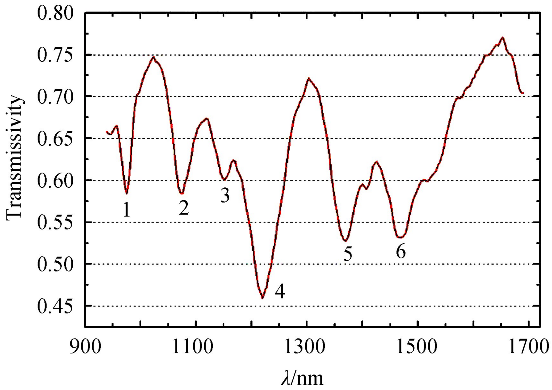


Fig.6 Transmissivity spectra of SRM-2035a

Table 2 Deviation of the wavelength calibration tested by SRM-2035a

Absorption peak	Standard wavelength/nm	Calibrated wavelength/nm	Deviation/nm
No.1	975.8 ± 0.1	975.0	0.8
No.2	1 075.6 ± 0.1	1 076.0	0.4
No.3	1 151.5 ± 0.1	1 152.1	0.6
No.4	1 222.2 ± 0.2	1 221.2	1
No.5	1 366.8 ± 0.1	1 368.1	1.3
No.6	1 469.1 ± 0.2	1 469.2	0.1

We also test the response of a 1 389 nm single-mode distributed feedback laser with the spectral micro-module. Without the temperature control unit, the laser's temperature drift has great influence on the peak wavelength accuracy. But the FWHM can be still taken as a verification of spectral resolution. As shown in Fig. 7, the test value of peak wavelength and FWHM are 1 386.8 nm and 14.9 nm. The FWHM is less than 1.25% of the peak wavelength, which is in agreement with the calibration results.

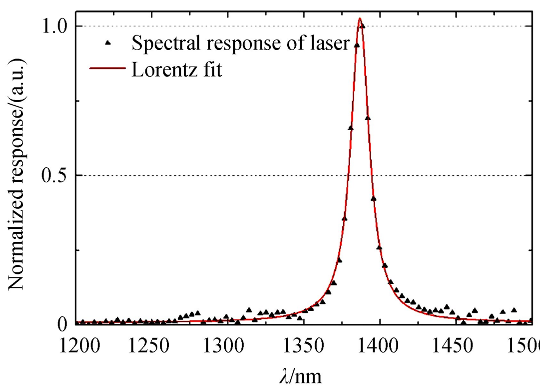


Fig.7 Spectral response of a 1 389 nm single-mode distributed feedback laser

For higher utilization efficiency, the size of LVF should be custom-designed to cover all the 256 pixels. Moreover, the wavelength calibration method we used did not involve any complicated mathematical calculation and could be used in all kinds spectrometer's calibration, it was still too complex to adopt in mass production. As shown in Fig.5, the wavelength distribution of pixels can be seen as linear benefiting from the LVF's uniformity. Thus, simplified calibration method for the LVF integrated spectral micro-module can be explored based on the standard reference material and high-precision laser.

3 Conclusion

An integrated spectral micro-module with an LVF and an InGaAs focal plane array was reported. The spectral range is from about 900 nm to 1 700 nm, with the FWHM of each pixels distributing between 11 nm and 16nm. A wavelength calibration method and its accuracy verification were both proposed. The calibration accuracy is tested to be less than 1.3 nm and the spectral resolution is no larger than 1.25% of peak wavelength. The results confirm that the method of wavelength calibration is feasible and accurate. With the compact structure and stable optical properties, the spectral micro-module can be widely used in field or on-line applications.

References

[1] ZHANG Bing, WANG Xiang-jun, LIU Jian-gui, *et al*. Hyperspectral image processing and analysis system (HIPAS) and its application[J]. *Photogrammetric Engineering & Remote Sensing*, 2000, **66**(5): 606-609.

[2] SAMBONGI M, IGARASHI M, OBI T, *et al*. Analysis of spectral reflectance using normalization method from endoscopic spectroscopy system[J]. *Optical Review*, 2002, **9**: 238-243.

[3] HUANG Xing, LI Xue, SHI Ming, *et al*. The 1/f noise characteristics of $In_{0.83}Ga_{0.17}As$ photodiodes with SiNx passivation films fabricated by two different techniques [J]. *Infrared Physics & Technology*, 2014, **67**: 596-599.

[4] YANG Jing, SHI Ming, SHAO Xiu-mei, *et al*. Low leakage of $In_{0.83}Ga_{0.17}As$ photodiode with Al_2O_3/SiN_x stacks[J]. *Infrared Physics & Technology*, 2015, **71**: 272-276.

[5] QIN Hong, MA Jing-yi, CHEN Shao-jiang, *et al*. Identification of haploid maize kernel using NIR spectroscopy in reflectance and transmittance modes: a comparative study[J]. *Spectroscopy and Spectral Analysis*, 2016, **36**(1): 292-297.

[6] LUYPAERT J, ZHANG M H, MASSART D. Feasibility study for the use of near infrared spectroscopy in the qualitative and quantitative analysisof green tea, Camellia sinensis[J]. *Analytica Chimica Acta*, 2003, **478**(1): 303-312.

[7] CHU Xiao-li, LU Wan-zhen. Research and application progress of near infrared spectroscopy analytical technology in China in the past five years[J]. *Spectroscopy and Spectral Analysis*, 2014, **34**(10): 2595-2605.

[8] WANG Xu-quan, HUANG Song-lei, YU Yue-hua, *et al*. A compact long-wavelength near-infrared IOT node and its performance experiments[J]. *Journal of Infrared and Millimeter Waves*, 2018, **37**(1): 57-61.

[9] CHU Xiao-Li. Handbook of Near-Infrared Spectral Analysis Technology[M]. Beijing: China Machine Press, 2016: 15-29.

[10] NADA A, CHARLES A, DONALD M, *et al*. Miniature near-infrared (NIR) spectrometer engine for handheld applications[C]. SPIE, 2012, **8374**: 837404.

[11] DONALD M, CHARLES A, MARC G, *et al*. Miniature near-infrared spectrometer for point-of-use chemical analysis [C]. SPIE, 2014, **8992**: 899203.

[12] LI Xue, GONG Hai-mei, FANG Jia-xiong, *et al*. The development of InGaAs short wavelength infrared focal plane arrays with high performance[J]. *Infrared Physics & Technology*, 2017, **80**: 112-119.

[13] ZHANG Ya-guang, ZHUANG Xin-gang, WANG Xu-quan, *et al*. Wavelength calibration of a new monolithically integrated spectral sensor[J]. *Journal of Infrared and Millimeter Waves*, 2017, **36**(15): 15-19.

[14] DAVID L, STEVEN J, LINDSEY O, *et al*. Rare-earth glass reference materials for near-infrared spectrometry: sources of x-axis location variability[J]. *Analytica Chimica Acta*, 2003, **490**: 85-98.

[15] STEVEN J C, JOHN C T, DAVID L D. cSRM 2035: a rare earth oxide glass for the wavelength calibration of near infrared dispersive and Fourier transform spectrometers[C]. SPIE, 1998, **3425**: 94-102.