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Freeform lens collimating spectrum-folded Hadamard transform near-infrared spectrometer

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ABSTRACT

A novel Hadamard transform spectrometer collimated by a freeform lens has been designed, which doubles the working spectral range while the spectral resolution is maintained. The freeform lens is designed to redistribute the broadband spectra of the source from 800 nm to 2400 nm into two collimated beams with different wavelengths and different tilting angles, to achieve the folding of spectra on the digital micro-mirror devices (DMD). It is constructed by solving two partial differential equations. The grating diffraction efficiency of the two split beams are more uniform and higher compared with the traditional method. The simulation results show that the bandwidth of the spectrometer is doubled and the spectral resolution is better than 10 nm. The optical system becomes more compact, and the energy efficiency is improved by 11.98% by folding the spectra with one freeform lens and one grating.

1. Introduction

Near-infrared spectroscopy is becoming a well-established analytical method to achieve quality monitoring and product analysis in a wide range of applications ranging from agriculture to petrochemical industry and also clinical medicine areas [1–3]. In many cases, it's important to measure the spectra with high resolution and wide working wavelength range. For example, to identify the quality of milk powder or medicinal material, a spectrometer which has a wavelength range of 800–2500 nm with a resolution better than 10 nm is necessary to make the measurement accurately and precisely [4]. However, most of the commercially available near-infrared spectrometers can't achieve high resolution and wide working wavelength range at the same time, such as AvaSpec-NIR256-2.2 which has a spectral resolution of 15 nm at working wavelength range of 1000–2200 nm. This kind of situation has hindered the widespread use of portable near-infrared spectrometer.

In a previous publication [5], we doubled the working wavelength range of a portable Hadamard transform spectrometer (HTS) with no decrease of the spectral resolution by using two sub-gratings tilting with different angles. The spectral resolution was 5.5 nm while the working wavelength range was from 800 nm to 2000 nm. However, in its practical implementation, there are some limitations with respect to the stray light caused by the two sub-gratings and the precision of the sub-grating integration, especially when the number of sub-gratings increases to several tens [6]. Based on those findings, we propose a novel optical system which not only reduces the complexity of the spectrometer, but also improves the optical performance.

Compared with traditional optical components, freeform optics can precisely control the distribution of light beams, and simplify the system with fewer surfaces, lower mass which reduces the difficulty in assembly [7–10]. In this study, we propose a novel source collimating approach by using freeform lens to extend the working wavelength range. The freeform lens is designed to redistribute the light from source into two collimated beams in different directions with different wavelength regions, from 800 nm to 1600 nm and from 1600 nm to 2400 nm, respectively. Then only one plane grating is used to fold the spectra on DMD. The main contribution of this article is presented in Section 2: the derivation of the incident angles of the two collimated beams and the calculation and construction of the freeform surface. The diffraction efficiency of the grating is optimized to be more uniform and higher over the entire band. The optical layout and simulation

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results are showed in Section 3. By folding the two bands on DMD, the working spectrum range of the spectrometer is doubled while the resolution is maintained. The spectral resolution is better than 10 nm and the diameter of the single element detector is smaller than 4 mm. The simulation results show that the optical system of this spectrometer becomes more compact, and the energy efficiency is improved by 11.98%. What's more, the secondary spectra of the spectrum-folded spectrometer are much easier to be eliminated compared with traditional broadband spectrometers.

2. Design method of novel source collimating approach

2.1. The derivation of the incident angles

As an improvement, here a freeform lens is designed to redistribute the irradiance from optical fiber into two collimated beams in different directions propagating towards the grating, as shown in Fig. 1. Then the two dispersed beams are focused onto the DMD by imaging lens, folding the entire working spectrum into two parallel and aligned spectral stripes on DMD with only one grating. The DMD composed of a micro-mirror array of 1024 × 768, and each mirror rotates either +12° or −12° axis to the diagonal line according to the code of Hadamard matrix [11]. It is used as the mask of Hadamard transform to implement the spectrum encoding. The modulated spectrum are reflected by DMD and focused by the converging lens onto a single element detector. The original spectra of the source are acquired by the decoding of Hadamard transform [12].

In this work, the working spectra of the HTS, λ_1 to λ_3, is divided into two bands with equal bandwidth of the wavelength window, λ_1 to λ_2 (band A) and λ_2 to λ_3 (band B), corresponding to the two spectral columns folded on DMD respectively. The incidence angles onto the plane grating are the same for all the wavelengths of band A, so as band B. The grating equation yields:

$$\sin\delta_{\text{Amax}} - \sin\delta_{\text{Amin}} = \frac{m(\lambda_2-\lambda_1)}{d} = \frac{m\Delta\lambda}{d}, \tag{1}$$

$$\sin\delta_{\text{Bmax}} - \sin\delta_{\text{Bmin}} = \frac{m(\lambda_3-\lambda_2)}{d} = \frac{m\Delta\lambda}{d}, \tag{2}$$

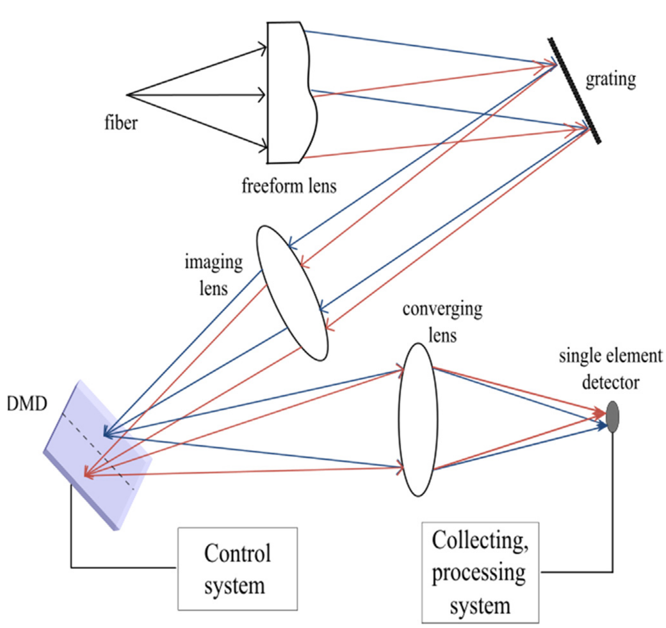

Fig. 1. Schematic layout of the spectrum-folded near-infrared HTS.

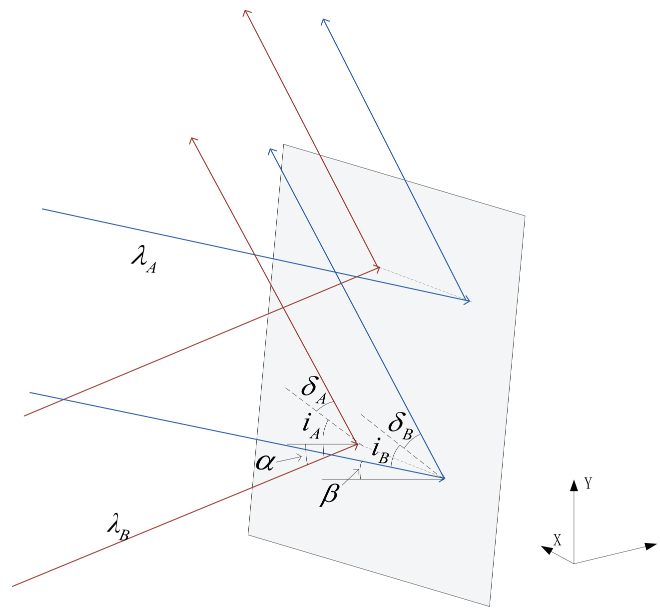

Fig. 2. Schematic of the light diffraction of bands A and B on the grating.

where δ_{Amax}, δ_{Amin} , δ_{Bmax}, δ_{Bmin} are the maximum and minimum diffraction angles of spectra in band A and B, respectively. m is the order of diffraction and d is the groove space of the grating. From Eqs. (1) and (2), it can be concluded that the spectra of band A and B are distributed within the same range of the diffraction angles when the value of m and d is specified.

After being collimated by the freeform lens, rays of band A and band B are incident on the grating with different angles i_A and i_B, as shown in Fig. 2. δ_A and δ_B are the diffraction angles of λ_A and λ_B, which are the corresponding central wavelengths of band A and B, respectively. α is the angle between the collimated beam of band A and Z axis. β is the angle between the collimated beam of band B and Z axis. Z axis is the optical axis of the system. In order to align the corresponding spectra of the two bands on the DMD surface, their diffraction angles should be the same, which means $\delta_A=\delta_B$. Then the relationship between the incidence angles and the wavelengths can be derived as:

$$\sin i_A - \sin i_B = \frac{m(\lambda_A-\lambda_B)}{d}. \tag{3}$$

According to Eq. (3), the value of i_A can be calculated once the value of i_B is specified, and vice versa. When the angle between the grating normal and the Z axis is specified, the tilt angles of the two collimated beams can be derived, which are essential to the ray tailoring calculation of the freeform surface.

2.2. Calculation and construction of the freeform lens

To simplify the mathematical model, two assumptions are made: (1) the front surface of the freeform lens is spherical and centered at the origin of the coordinate; (2) a point source located at the center of the sphere is adopted as the source. A ray sent out from the source is incident on the front surface perpendicularly and intersects with the freeform surface at point P. The coordinate of point $P(P_x, P_y, P_z)$ can also be expressed as $P(\rho(\theta,\varphi),\theta,\varphi)$ in the spherical coordinate system. The ray from point P strikes the grating at point $G(x, y, z)$. Fig. 3 illustrates how a ray from the point source is uniquely tailored to a point on the grating plane. $\boldsymbol{I}$, $\boldsymbol{O}$ and $\boldsymbol{N}$ are the incident, refractive and normal unit vectors at point P, respectively. They can be expressed as: $\boldsymbol{I}= (I_x\boldsymbol{e}_x, I_y\boldsymbol{e}_y, I_z\boldsymbol{e}_z)= (\sin\varphi\cos\theta\boldsymbol{e}_x, \sin\varphi\sin\theta\boldsymbol{e}_y, \cos\varphi\boldsymbol{e}_z)$ and