A Novel MOEMS NIR Spectrometer

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Abstract

In order to detect luminous intensity of light signal in NIR (Near-infrared) wavelength range, a novel MOEMS(Micro-Opto-Electro-Mechanical Systems) NIR spectrometer is proposed in the paper. It uses DMD (Digital Micro-mirror Device) to band filter the input spectrum. The merits of DMD are small size, low price and high scan speed. Especially, when DMD acts as a Hadamard Transform encoding mask, the SNR (signal-to-noise-ratio) can be improved by multiplexing the light intensities. The structure and the theory of this spectrometer are analyzed. The Hadamard-S matrix and mask of 63-order and 127-order are designed. The output spectrum of the new spectrometer coincides with experimental result of Shimadzu spectrometer. The resolution of the new spectrometer is 19nm over the spectral range between 900~1700nm while single scan time is only 2.4S. The SNR is 44.67:1. The size of optical path is 70mm×130mm, and it has a weight less than 1Kg. It can meet the requirement of real time measurement and portable application.

1. Introduction

The near-infrared spectrum technology which measures materials by the absorption of resonating frequencies according to Lambert law, with the advantages of nondestructive detection, fast speed and convenience, widely applies in many domains, such as optics examination, biochemistry analysis, industry automatic detection, astronomy research and so on. Usually, the luminous intensity of light signals in NIR(Near-infrared) wavelength range can not be easily detected in most micro spectrometers, which often enhance the spectrum resolution by narrowing the entrance slit. HT (Hadamard Transform) spectrometer has multiplex advantage to solve this problem effectively by replacing the entrance slit with a Hadamard encoding mask\cite{1}.

The typical HT encoding mask are mechanical mask, LC-SLM (Liquid Crystal-Spatial Light Modulator) mask, MOEMS(Micro-Opto-Electro-Mechanical Systems) mask etc. Mechanical mask originates from dynamic multi-slit spectrometer\cite{2}. It modulates the spectrum by shift the mask repeatedly. This mask doesn’t absorb the light, so there

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are only two states (transmission or non-transmission) to modulate the light without loss, so the encoding data don’t need correction, and the fabrication of this mask is simple. But the shift speed is low, and the position error will be brought as driven by stepping motor. LC-SLM mask has the advantage of high modulation speed and no movable parts, which overcomes the shortages of mechanical mask. However, as the light absorption of liquid crystal, and the variable of transparency to difference wavelength light, the coding error and signal loss will be caused by using LC-SLM mask[3]. As the developing of MOEMS, micro-mechanical slit array[4] emerges to overcome the shortcomings of HT encoding mask above. But the number of slits is limited by the mask size and actuator capacity. In this paper, a novel MOEMS NIR spectrometer is proposed, which use DMD(Digital Micro-mirror Device) as HT encoding mask, DMD has no errors induced by vibration and erosion as mechanical mask, and has the merits of high modulation speed, broad modulation spectrum range, and high efficiency in contrast to LCD mask. The new spectrometer can enhance resolution by programming the DMD mask with high order HT mask, and has multiplex advantages of high light intensity.

2. Structure and operating theory of new MOEMS NIR spectrometer

The new MOEMS NIR spectrometer has simple structure shown in Fig.1. Firstly, the radiation of light source passes the sample pool to get the information of sample. Secondly, after dispersion of light by a fixed grating, the spectrum signal is band filtered by DMD. DMD allows special combinational light channels to be turned on. Finally, the total intensity of these light beams is focused onto a single detector. The HT encoding mask patterns are loaded into the micro-mirrors array N times in a measurement round. An estimate of the input spectrum can be recovered from the results via the inverse Hadamard transform. If the detector noise is independent of the intensity of radiation, the output SNR of a HT spectrometer with N resolution elements can be larger than the output SNR of a monochromator by a factor about $\sqrt{N}/2$. So it can not only solve the problem of luminous flux but also settle the conflict of resolution and signal-to-noise ratio, increase the SNR effectively.

![Fig.1 The system of new MOEMS NIR spectrometer](image)

3. Hadamard transform theory and realization by DMD

In conventional spectrometer, detector only samples single wavelength signal at a time. But in HT spectrometer, it samples the sum of the multi-wavelength signals. The theoretical model of HT is based on $N \times N$ matrix equations developed by mathematician Jacques S. Hadamard [5].

$$y_j = \sum_{i=1}^{n} S_{ij} \cdot x_i$$

(1)
Here \( y_j \) is the signal encoded by the mask \( j \), and \( x_i \) is the signal of wavelength \( i \), and the vector \( S_{ij} = (S_{ij}, S_{ij}, \ldots, S_{ij}) \) consists of 1 or 0, which denotes turning on or turning off the correspond light channel.

Translate above equation into the form of matrix:

\[
Y = S \cdot X
\]  

Using inverse Hadamard transform, the result of input spectrum is:

\[
X = S^{-1} \cdot Y
\]

Here the vector \( X \) is the original spectrum signal, each element of vector corresponds to different wavelengths. The vector \( Y \) is the detection signal encoded by HT. \( S \) is Hadamard matrix. Comparing to the single slit spectrometer, the theoretical reduction in the noise components of the measurements are approximately \( \sqrt{\frac{1}{N}} \) for HT spectrometer with the use of a cyclic S-type encoding matrix. How to realize the S matrix is the key to HT spectrometer. The DMD is selected to be S matrix encoding mask here by the reasons below.

DMD is a type of MOEMS device which has been commercially available by Texas Instrument for display application[6]. The DMD consists of 1024×768 array of micro mirror in size of 10.8μm. Each mirror can be individually deflected at ±10° which is controlled by changing the binary state of underlying CMOS control circuit and reset signals. So we can use DMD as a light modulator, as shown in Fig.2, which will realize the HT encoding modulation of light by loading the codes of HT mask to the DMD. The seesaw action style makes the turning angle repeat precisely. DMD has a high reflectivity by sputtering \( Al \) film and a high turning speed about 2μs. The 63-order or 127-order Hadamard-S matrix can be easily loaded into DMD by programming the control FPGA(Filed Programmable Gate Array) of DMD( see Fig. 3).

Fig. 2 The modulation principle of DMD                      Fig. 3 The 63 and 127 order S matrix and realization in DMD

4. Experiment

To verify the theory of new MOEMS HT spectrometer, a prototype is built as shown in Fig.4. The structure has explained in details in Fig. 1. The size of optical path is 70mm×130mm, and weight of the instrument is under 1Kg. Standard filters as samples are measured. After processing the output signal detected by single PbS detector, the spectrum signal is acquired. Here the DMD is controlled by program in two modes to modulate the spectrum for comparing: Single line scan mode to simulate traditional raster scan spectrometer and HT scan mode to verify new instrument theory. In the HT scan mode, a 63-order Hadamard-S matrix encoding mask is adopted and the scan time is 2.4S. In fact, the time can be further reduced by programming DMD easily. But fast scan speed may lead to bad SNR. The results are compared in Fig. 5. Fig.5(a) shows that under single line scan mode, the root mean square signal-to-noise ratio(the ratio of most intense line to the root mean square noise [3] ) SNR1=13.28 : 1. Fig.5(b) shows that under HT scan mode, the root mean square signal-to-noise ratio SNR2=44.67 : 1. According the formula \( G=\text{SNR2}/\text{SNR1} \), the signal-noise-ratio gain is approximately 3.4. Comparing to theoretical signal-noise-
ratio gain formula $G^* = \sqrt{N/2} = 3.97$, the result is close. The difference is mainly caused by the increased photon noise due to the increased light intensity in the HT mode.

Furthermore, a comparing of the measured spectra with Shimadzu IRPrestige-21 spectrometer is carried out. The huge instrument of Shimadzu IRPrestige-21 has a fine resolution of 4cm$^{-1}$. After calibration, the results (see Fig. 6) show that final spectrum of the new MOEMS NIR spectrometer coincides with experimental result of Shimadzu spectrometer. And the new spectrometer have resolution of 19nm over the spectral range between 900~1700nm. Although the parameters are not as good as big instrument, but they are typical in the micro-spectrometers and can satisfy the analysis about protein etc.. The experiment verified the theory of the new MOEMS NIR spectrometer and proved it can measure faint light signal in the wavelength range of NIR.

5. Conclusion

A novel MOEMS NIR spectrometer is proposed and tested in this paper. With the core device of DMD acted as Hadamard Transform encoding mask, it has the multiplex advantage to enhance the resolution without degrading SNR. It also has the merits of fast modulation, wide spectrum, minor abrasion and errors etc. The structure and theory of this spectrometer are analyzed. And the Hadamard-S matrix is realized by DMD development kits. Experiments show that the output spectrum of the new spectrometer coincides with measured result of standard spectrometer. The parameters of new spectrometer can meet the requirement of real time measurement and portable application.
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Reference