Design and experimental research on a visible-near infrared spatial modulating Fourier transform spectrometer based on micro multi-step mirrors*

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A type of spatial modulating micro Fourier transform spectrometer (FTS) based on micro multi-step mirrors (MMSMs) is designed and manufactured in this paper. The interference system is based on Michelson interferometer, using two MMSMs instead of plane mirrors in two arms. The recovered spectrum is simulated with different distances between MMSMs and the detector, and the influence of diffraction on the recovered spectrum is analyzed. The edge-enlarging method for the MMSMs is proposed to eliminate edge noise, and the influence of surface roughness of MMSMs on the recovered spectrum is also analyzed. Moreover, the way of manufacturing the MMSMs is investigated.

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Recently, the micro Fourier transform spectrometer (FTS) with advantages of small volume, light weight and pocket taking is developed rapidly because of its wide applications in spectral measurement[1-3]. FTS is classified into two types by principle, namely, temporal modulating FTS and spatial modulating FTS. The studies of micro FTS in recent years are mainly based upon temporal modulation[4-10]. Temporal modulating spectrometer requires highly precise moving mirror driven system to control the movement of mirror, and change its position so as to obtain interferograms at different time. The precision of manufacture and assembly should be more strict due to the existence of movable parts which can also cause poor repeatability and stability. Temporal modulation cannot realize real-time measurement[11-14] because data processing must be after one scanning cycle of the moving mirror. Compared with temporal modulation, the micro FTS based on spatial modulation without movable parts has advantages of compact structure, good stability, high reliability, and real-time measurement of spectrum.

In this paper, a spatial modulating micro FTS based on micro multi-step mirrors (MMSMs) is designed and analyzed, whose interference system is based on Michelson interferometer, using two MMSMs instead of plane mirrors in two arms. This structure without moving mirror scanning system can realize real-time measurement.

The structure of the optical interference system is shown in Fig.1. In this system, two MMSMs, M_1 and M_2 are used to replace two plane mirrors in Michelson interferometer. The two MMSMs, placed orthogonally, both have m sub-mirrors and the step heights are d and md, respectively. Light beams transmit through the collimation system to the beam splitter, divided into two coherent light beams with equal intensity: one beam is reflected by the beam splitter to M_1, and then reflected back by M_1 to detector through beam splitter; the other beam transmits through beam splitter to M_2, and then is reflected by M_2 and beam splitter to the detector. Reflected beams from each step of M_1 and M_2 interfere at different positions in the space, and form m^2 interference regions. The information of each interference space is received by different pixels in the CCD, and the spectrum information of the measured signal could be recovered via the Fourier transform.

The simplified model is shown in Fig.2. The collimation system is omitted in this model, because the light from the source is set as parallel. The interference light forms m^2 interference regions on the detector, and the interferogram image is shown in Fig.3. Collecting interference intensity data from interferogram image and cor-

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responding to optical path differences could get the recovered spectrum via Fourier transform, shown in Fig.4.

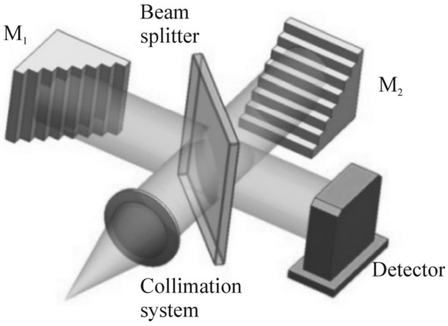


Fig.1 Structure of the optical interference system

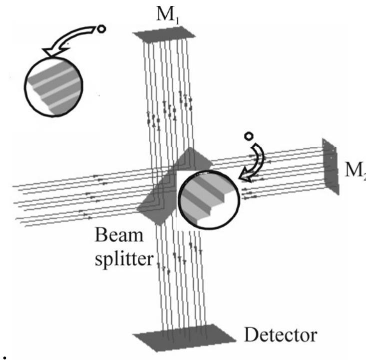


Fig.2 Simplified structure for simulation

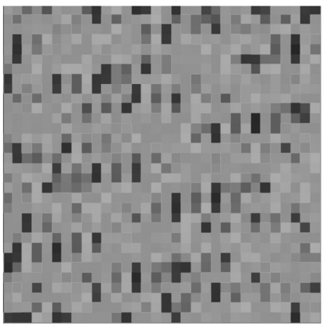


Fig.3 Interferogram image

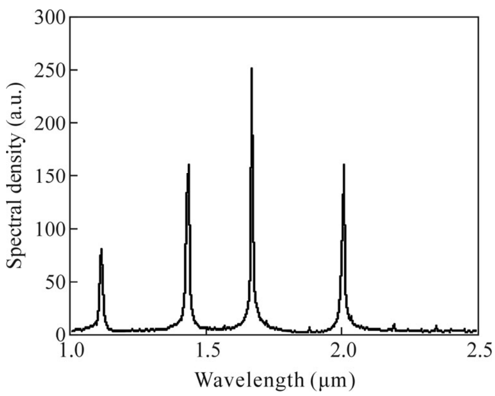


Fig.4 Recovered spectrum

In order to reduce diffraction effects, the widths of sub-mirrors in MMSMs should be 100—1000 times of the maximum detected wavelength[8], but the diffraction effect still influences the recovered spectrum. Demonstrated by the Fresnel diffraction model, the longer the distance L between MMSMs and the detector is, the stronger the diffraction effect is. In this paper, the influence of diffraction effect on the recovered spectrum simulated with different distances between MMSMs and detector is analyzed.

Fig.5(a) shows the recovered spectrum without considering diffraction, where the spectrum does not change with the distance L. Fig.5(b) is the recovered spectrum considering diffraction, in which L=5 cm. We can see that diffraction effect intensifies and the noise of recovered spectrum becomes larger when the distance L increases. The minimum distance between MMSMs and detector depends on the size of the beam splitter. In this structure, the size of the beam splitter is about 2.5 cm$\times$2.5 cm$\times$2.5 cm, so MMSMs could be placed close to the beam splitter, and the distance L could be controlled within 3—4 cm. As analyzed above, the influence of diffraction effect on spectrum recovering could be ignored.

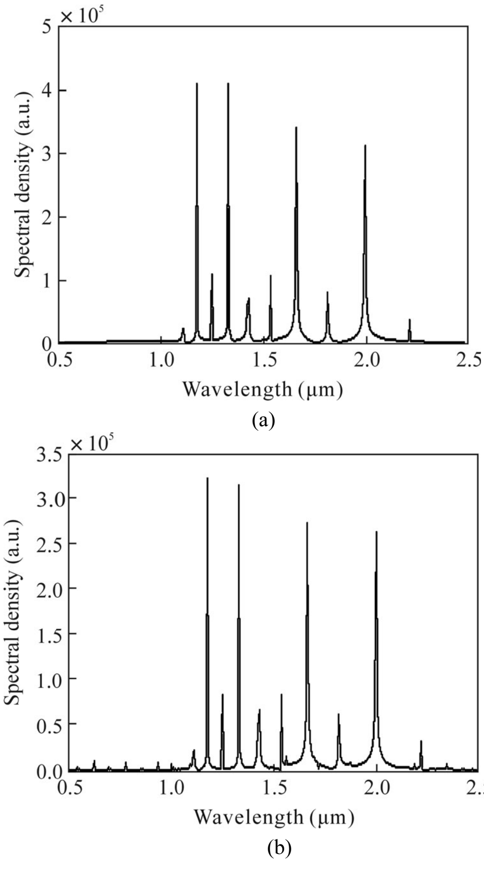


Fig.5 Simulated recovered spectra (a) without considering diffraction effect and (b) considering diffraction effect when *L*=5 cm

The noise caused by different reasons in the interference region is called edge noise. With the purpose of eliminating edge noise, the collected interference regions should be in the same status, namely, not at the edge of the interferogram image. So an edge-enlarging method for MMSMs is designed: Lengthening both sides of the MMSMs, and adding a sub-mirror outside the first and the last steps. The parameters of the adding steps are the same as those of primary steps. The interference regions and the corresponding optical path differences before and after edge-enlarging are shown in Fig.6.

L2 \ L1	0	1	2
2	2	1	0
5	5	4	3
8	8	7	6

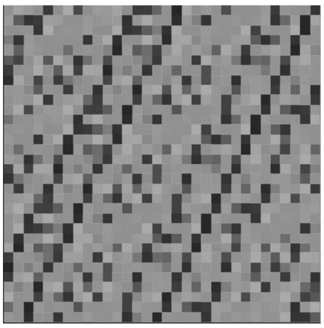
(a)

L2 \ L1	-1	0	1	2	3
-1	0	-1	-2	-3	-4
2	3	2	1	0	-1
5	6	5	4	3	2
8	9	8	7	6	5
11	12	11	10	9	8

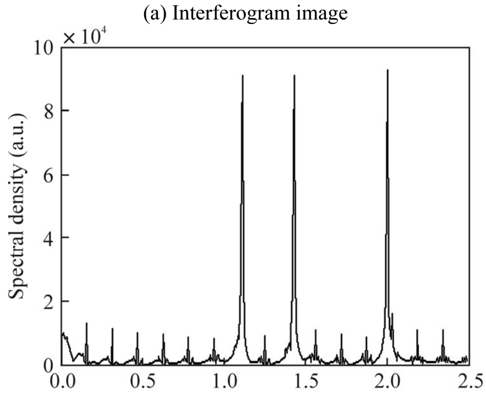
(b)

Fig.6 Interference regions and the corresponding optical path differences (a) before and (b) after edge-enlarging

The edge-enlarging method is simulated. The results without edge-enlarging are shown in Fig.7. The interferogram image without edge-enlarging is shown in Fig.7(a), and Fig.7(b) shows the spectrum with larger noise obtained via Fourier transform. Fig.8 shows the simulated results after adding two sub-mirrors in MMSMs. The interferogram image after edge-enlarging is shown in Fig.8(a), and the interferogram image inside the square frame is the required collecting region. The spectrum obtained via Fourier transform is shown in Fig.8(b), and the noise is restrained obviously.



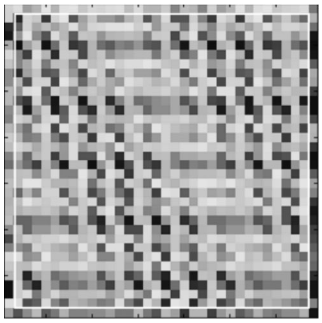
(a) Interferogram image



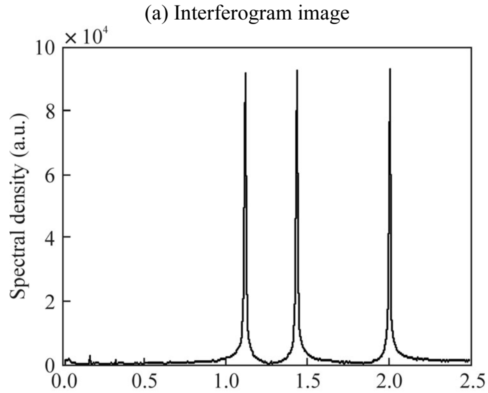
(b) Recovered spectrum

Fig.7 Interferogram image and the recovered spectrum before edge-enlarging

The two MMSMs can reflect the beams coming from the beam splitter and produce optical path differences. The surface roughness of sub-mirrors influences the interferogram image directly, and furthermore, it influences the recovered spectrum. The surface roughnesses of two MMSMs are set as 5 nm and 10 nm in Fig.9(a), 15 nm and 40 nm in Fig.9(b), respectively. The simulated recovered spectrum indicates that the noise increases with the surface roughness. According to the simulation results and analysis, the maximum tolerances of surface roughness of MMSMs are set as 10 nm and 30 nm, respectively.



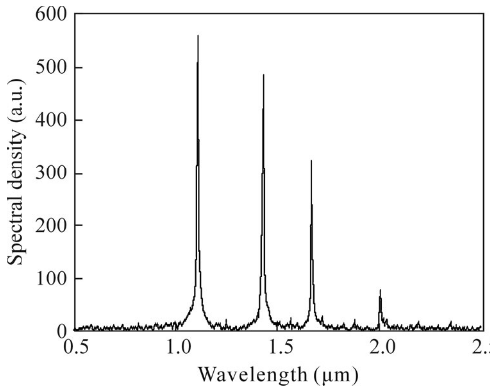
(a) Interferogram image



(b) Recovered spectrum

Fig.8 Interferogram image and the recovered spectrum after adding two edges

The manufacture level and quality of the MMSMs will determine the quality and capability of the whole system. After experimental research and analysis, the method of depositing multi-layer in fixed areas is chosen to manufacture the MMSMs. The first step is depositing a layer on the substrate, and then depositing layers successively. The width and thickness of each layer are half of those of the last layer. By using this method, the MMSMs with 2^P sub-mirrors (P is the time of depositing multi-layer in fixed areas) could be manufactured. Reflective coatings are deposited or sputtered on the structure to achieve the requirement of reflectivity.



(a)

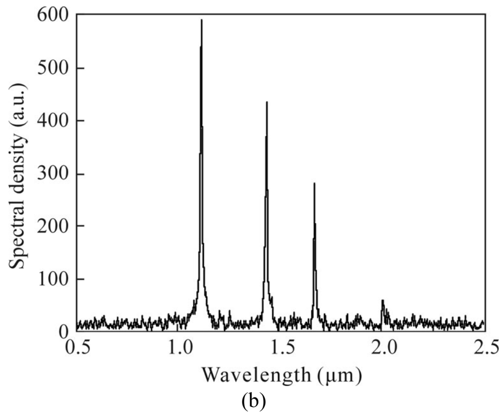


Fig.9 Recovered spectra with different surface roughnesses of MMSMs: (a) 5 nm, 10 nm; (b) 15 nm, 40 nm

Fig.10 is the photo of MMSMs without depositing reflective coatings. The testing result of step surface roughness is shown in Fig.11, by using atomic force microscopy (AFM). It indicates that the step height of MMSMs is feasible, and the RMS of surface roughness in sub-mirrors is 3.1 nm.

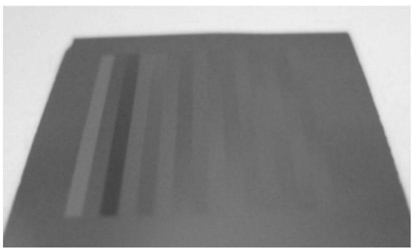


Fig.10 Photo of MMSMs without depositing reflective coatings

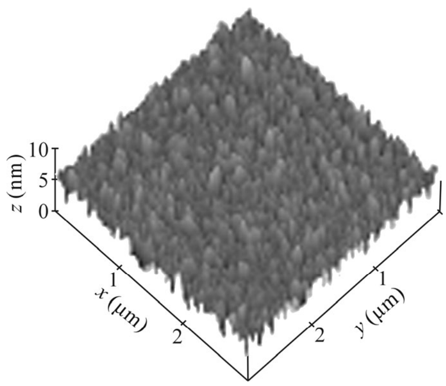


Fig.11 AFM testing result of surface roughness of the MMSMs

The structure parameters of interference system in the FTS based on MMSMs are simulated and analyzed by establishing a simplified model for the interference system. The influence of diffraction effect on the recovered spectrum is so little that it could be ignored. The edge noise of MMSMs is researched and an edge-enlarging method to restrain edge noise is proposed. The maximum tolerances of surface roughness of MMSMs are 10 nm and 30 nm, respectively. MMSMs are manufactured by the method of depositing multi-layer in fixed areas and the RMS of surface roughness is 3.1 nm tested by atomic force microscopy, which satisfies the design requirement of the system.

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