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Fabrication and analysis of tall-stepped mirror for use in static Fourier transform infrared spectrometer

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ABSTRACT

A method of "slope splicing" is proposed to build a tall-stepped mirror with high precision in a stepped-mirror-based static Fourier transform infrared spectrometer. The structural parameters were designed, and their errors were analyzed. We present the test results and an analysis of the combined effect of the errors on the recovered spectrum. The spectrum-constructing error of the constructed spectrum, 5.81%, meets the requirements for the system and suitable for realization of a miniaturized spectrometer. We performed experiments with the tall-stepped mirror to obtain the interferogram and spectrum of a silicon carbide light source. Further work is needed to optimize the capability of the system.

1. Introduction

Spectrometers are widely used in many fields, including chemical analysis, environmental monitoring, and space exploration. Fourier transform spectrometers (FTSs) are favored because of their high luminous flux and multi channel transmission capacity [1–3]. Most industrial FTSs are time-modulated and equipped with a moving plane mirror. However, the movement precision and system stability are still large problems [4]. A space-modulated FTS based on a Michelson interferometer with the two plane mirrors replaced by two stepped mirrors was proposed by Möller in 1992 [5,6] and studied at other institutions [7–9]. With advances in technology, miniaturized and lightweight FTSs became urgently necessary, and we proposed a micro static Fourier transform infrared (FTIR) spectrometer based on micro-optical electro-mechanical system (MOEMS) technology [10]. Compared with other micro FTSs, it has significant advantages of stability, a simplified configuration, and excellent repeatability because it has no moving components.

As the core components of FTIR spectrometer, two stepped mirrors play an important role in sampling the interferogram at different optical path differences (OPDs); the spectrum is then obtained through Fourier transform of the interferogram. However, the Fourier transform requires exactly equal sampling intervals, and the obtained spectrum is crucially sensitive to the sampling errors [11]. For a tall-stepped mirror (TSM), the step height error and sub-mirror width error produce nonuniform samples in the interferogram [12,13], and the sub-mirror angle error causes variation in the OPD [14]. Furthermore, the roughness of the reflecting surface will produce spectral artifacts. Therefore, the TSM requires a highly precise surface, which is difficult to manufacture [15].

Many technologies for fabricating a short-stepped mirror with step height 0.625 μm have been discussed in early research [15,16], whereas it is helpless to the taller steps. It has been difficult to build a TSM with a step height of 20 μm. In this paper, a simplicity and cost-effective method of building a TSM by "slope splicing" is proposed and realized. The errors in the structural parameters of the TSM, i.e., the step height, sub-mirror width, sub-mirror tilt angle, and roughness of the reflecting surface, were analyzed and tested, and their combined effects on the recovered spectrum were discussed. Finally, experiments were performed with the TSM used in the static FTIR spectrometer to obtain the interferogram and recovered spectrum for a silicon carbide light source.

2. Principle of the FTIR spectrometer

Fig. 1 shows a schematic drawing of the configuration of the static FTIR spectrometer, which is based on Michelson's interferometer with

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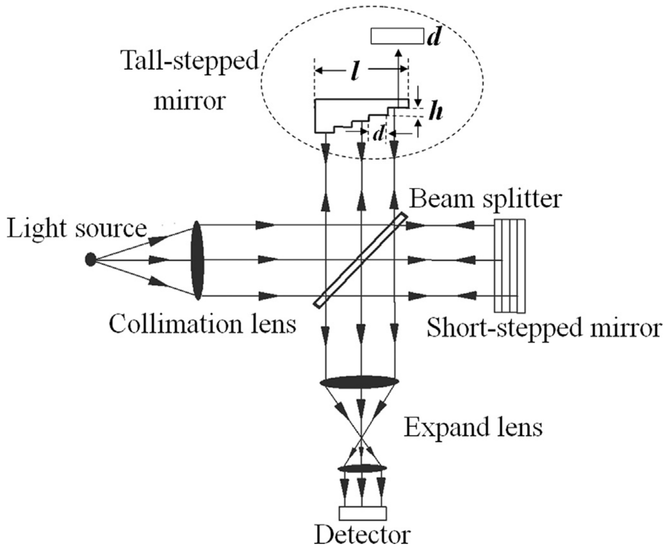

Fig. 1. Schematic drawing of configuration of the micro static FTIR spectrometer.

the two plane mirrors replaced by two crossed stepped mirrors each consisting of N steps. This paper focuses primarily on the TSM (dashed circle), where h is the step height, d is the sub-mirror width, and l and w are the effective length and width, respectively. The two stepped mirror heights are necessary to satisfy the Nyquist–Shannon sampling criterion and the principle of OPD continuity, i.e., that one tall step height corresponds to the sum of the steps of the short-stepped mirror. As a result, the system produces $N \times N$ samples with a uniform sampling interval of twice the step height of the short-stepped mirror. The interferometric function of a sample, which has been shown in [3], is

$$I(n,m) = \int_0^\infty B(\nu)\exp[j2\pi\nu\delta(n,m)]\mathrm{d}\nu. \quad (1)$$

$I(n, m)$ is the interferogram intensity at sample area (n, m), where n is the nth step of the TSM, and m is the mth step of the short-stepped mirror. $B(\nu)$ is the density of the power spectrum, ν is the spatial frequency of the optical signal, and $\delta(n, m)$ is the OPD on the spatial sampling area (n, m).

3. Design and error analysis of the TSM

3.1. Design

The structure of TSM is shown inside the dashed circle in Fig. 1. According to the Nyquist–Shannon sampling criterion, for the Nyquist frequency $\nu_{\max}$, the sampling frequency of the interferogram ν_{sample} must be greater than twice the greatest wavenumber. Thus, the sampling interval is smaller than half the minimum wavelength; i.e., $\Delta \le \lambda_{\min}/2$. To obtain a spectral resolution R, the sampling length L must be greater than the reciprocal of R (*i.e.*, $L \ge 1/R$), and the number of sampling areas N must obey $N \ge L/\Delta$.

The working wavelength of the system ranges from 2.5 to 12 μm; the number of samples is 1024, and the step height of the short-stepped mirror is 0.625 μm. Thus, the number of steps N is 32, and the step height h of the TSM is 20 μm. Considering the effect of diffraction, the sub-mirror width d is 1 mm [4], the effective length is l, and the overall width w is 32 mm.

3.2. Error analysis

The limited machining and locating precision of the sub-mirror during the fabrication process can cause the step height, sub-mirror width, sub-mirror angle, and surface roughness to deviate from the ideal values [14]. We analyzed the resulting distortion in the recovered spectrum.

The real spectrum different from the ideal spectrum that we call “the spectrum-constructing error (SCE)” was defined as

$$\text{SCE} = \frac{\sum_{k=0}^{N}\left|B_{\text{real}}(k) - B_{\text{ideal}}(k)\right|}{\sum_{k=0}^{N} B_{\text{ideal}}(k)}, \quad (2)$$

where $B_{\text{real}}(k)$ is the power of the real recovered spectrum, and $B_{\text{ideal}}(k)$ is the power of the ideal spectrum [11].

Given that the additional OPD introduced by the structural parameter errors of TSM is $\Delta\delta(n)$, according to Eq. (1), the light intensity distribution of the interferogram obtained by the detector is

$$I(n,m) = \int_0^\infty B(\nu)\exp\{j2\pi\nu[2(Nn-m)h + \Delta\delta(n)]\}\mathrm{d}\nu. \quad (3)$$

The real recovered spectrum with the errors is then obtained via the fast Fourier transform (FFT) in Eq. (3).

For the nth step, the step height error is $x(n)$, the width error is $\varepsilon(n)$, and the tilt angle error is $\theta(n)$, as shown in Fig. 2. When we consider only the step height error, $\Delta\delta(n)$ is

$$\Delta\delta_x(n) = 2x(n), \quad (4)$$

the width error is

$$\Delta\delta_\varepsilon(n) = 2\varepsilon(n)\tan\Phi, \quad (5)$$

the tilt angle error is

$$\Delta\delta_\theta(n) = 2d\ \tan\ \theta(n), \quad (6)$$

and the three errors together are

$$\Delta\delta(n) = 2\{x(n) + \varepsilon(n)\tan\Phi + [d + \varepsilon(n)]\tan\theta(n)\}, \quad (7)$$

Figs. 3–6 show the SCE theoretical value vs. the standard deviation of the step height, sub-mirror width, sub-mirror tilt angle, and surface roughness, respectively, of the TSM. For each structural parameter error, the TSM was generated and the spectrum was constructed 1000 times, and the SCE of each structural parameter's standard deviation was obtained by taking the

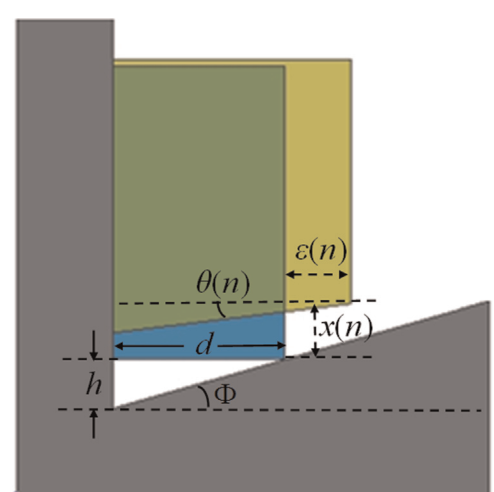

Fig. 2. Step height error, sub-mirror width error, and sub-mirror tilt angle error of nth step.