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Optical surfacing via linear ion source

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ABSTRACT

We present a concept of surface decomposition extended from double Fourier series to nonnegative sinusoidal wave surfaces, on the basis of which linear ion sources apply to the ultra-precision fabrication of complex surfaces and diffractive optics. The modified Fourier series, or sinusoidal wave surfaces, build a relationship between the fabrication process of optical surfaces and the surface characterization based on power spectral density (PSD) analysis. Also, we demonstrate that the one-dimensional scanning of linear ion source is applicable to the removal of mid-spatial frequency (MSF) errors caused by small-tool polishing in raster scan mode as well as the fabrication of beam sampling grating of high diffractive uniformity without a post-processing procedure. The simulation results show that optical fabrication with linear ion source is feasible and even of higher output efficiency compared with the conventional approach.

1. Introduction

As a state-of-the-art method of optical fabrication, ion beam figuring (IBF) [1] drives surface precision to extreme and applies to finishing lithography optics and telescope mirrors. In particular, one-dimensional (1-D) IBF [2], or sometimes called ion beam profiling [3], applies to the fabrication of elongated synchrotron optics such as aspherical X-ray mirrors. Compared with the conventional IBF, 1-D IBF is generally implemented by a simpler algorithm meanwhile the long-rectangular-shaped ion beam emitted from a linear ion source in 1-D case leads to higher output efficiency under the condition for ensuring similar finishing precision. To date, 1-D IBF is, however, only used in finishing 1-D optics and its applications are very limited though it has significant advantages.

Recently, to broaden its range of application in optical fabrication, we proposed a surface modeling method based on double Fourier series [4], which makes 1-D IBF feasible to figure or fabricate two-dimensional optical surfaces. Moreover, inspired by Zernike polynomials describing the relationship between surface errors and optical aberrations [5], we found that the modified Fourier series, or sinusoidal wave surfaces, build a relationship between the fabrication process of optical surfaces and the PSD-based surface characterization. The Fourier series decomposition of an optical surface produces a set of wave surfaces with a sinusoidal profile, which by and large are of different periods, amplitudes, and propagation directions. Conceptually, we can sequentially fabricate the decomposed wave surfaces by linear scanning with a linear ion source and the superposition of those fabricated wave surfaces finally build up a surface that approximates to the desired optical surface. In additional, the PSD analysis is actually the statistical analysis of the spatial-distributed wave surfaces described as components of double Fourier series and the PSD function is typically utilized [6], especially for evaluating surface errors in the MSF range.

This paper introduces the basic theory of surface modeling and decomposition, then illustrates the principle of optical fabrication with a linear ion source, and finally demonstrates two applications, i.e., the fabrication of large-aperture beam sampling gratings (BSGs) and the removal of errors in the MSF range.

2. Surface decomposition

A continuous smoothing surface $f(x,y)$ can be described as

$$f(x,y) = \sum_{m\in\mathbb{Z}}\sum_{n\in\mathbb{Z}} e^{i\omega_1 mx} C_{m,n} e^{i\omega_2 ny}, \tag{1}$$

where $f(x,y)$ is periodic by T_1 with coordicate X and T_2 with coordinate Y; $\omega_1 = 2\pi/T_1$, $\omega_2 = 2\pi/T_2$; $C_{m,n}$ is a complex number. In particular, $f(x,y)$ is a real function that is conjugate symmetric

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thus the imaginary part can be omitted. After adding a proper piston to every component, $e^{i\omega_1 mx}C_{m,n}e^{i\omega_2 ny}$, we get a slightly elevated surface, $S(x,y)$, that is suitable for indicating the spatial distribution of material removals and is displayed as

$$S(x,y) = \sum_{m\in\mathbb{Z}}\sum_{n\in\mathbb{Z}}(e^{i\omega_1 mx}C_{m,n}e^{i\omega_2 ny} + \mid C_{m,n} \mid), \tag{2}$$

where $\mid C_{m,n} \mid$ represents the piston or extra material removal; note that the arbitrary component $P_{m,n}(x,y) = e^{i\omega_1 mx}C_{m,n}e^{i\omega_2 ny} + \mid C_{m,n} \mid \geqslant 0$. Since ion etching is a subtractive process rather than an additive process, the desired material removal should be nonnegative thus it requires that $P_{m,n}(x,y) \geqslant 0$. Continued by Eq. (2), we put forward a new formula to decrease the number of scan strokes and improve the reachability of optical surfacing, which is represented as

$$S'(x,\ y) = \sum_{m\in\mathbb{Z}_{\geqslant 0}}\sum_{n\in\mathbb{Z}}(2P_{m,n} + \varepsilon_{m,n}), \tag{3}$$

where m and n not equal to 0 simultaneously; $\varepsilon_{m,n}$ denotes a small positive quantity and represents the compensated material removal. Since it exists an optimum removal in IBF process [7], $\varepsilon_{m,n}$ usually is not infinitesimal so that the scan speed is also properly limited. The component $P'_{m,n} = 2P_{m,n} + \varepsilon_{m,n}$, indicating the decomposed distribution of material removals, is shown as a sinusoidal wave surface, where the propagation direction is $\left(\frac{m}{T_1}, \frac{n}{T_2}\right)$ or $\left(-\frac{m}{T_1}, -\frac{n}{T_2}\right)$ and the period is $\left(\frac{m^2}{T_1^2} + \frac{n^2}{T_2^2}\right)^{-\frac{1}{2}}$.

2.1. Calculation of Fourier coefficients via Fast Fourier Transform

$$C_{M\times N} = \frac{\mathrm{FFT2}(S_{M\times N})}{MN}, \tag{4}$$

where $S_{M\times N}$ represents a material removal map by M times N, which is the discrete representation of $S'(x,y)$; two-dimensional Fast Fourier Transform (denoted as FFT2 hereafer) algorithm [8] is used for calculating the matrix of Fourier coefficients, $C_{M\times N}$. To exclude the DC component, $P_{0,0}$, it needs to assign that: $C_{M\times N}(1,1) = 0$.

2.2. Error analysis based on PSD function

The material removal map can be effectively approximated by the symmetric rectangular partial sum of double Fourier series [4]. The (m_1, n_1)th symmetric rectangular partial sum is defined as

$$S'_{m_1,n_1} = S'(x,y;m,n), \quad 0 \leqslant m \leqslant m_1, \quad 0 \leqslant\mid n \mid\leqslant n_1, \tag{5}$$

then we have the truncated errors

$$E_{m_1,n_1} = S'(x,y) - S'_{m_1,n_1}. \tag{6}$$

To evaluate the feasibility of the approximation, we use PSD function to analyze the truncated errors referring to as surface errors. The PSD analysis of the truncated errors can be implemented by the FFT2 algorithm, which is displayed as follows:

$$\mathrm{PSD}(E_{m_1,n_1}) = \frac{T_1T_2}{M^2N^2}\mathrm{FF,T2}(E_{m_1,n_1}). \tag{7}$$

3. Optical fabrication with linear ion source

Fig. 1 illustrates the basic principle of optical fabrication with linear ion source and also serves as a schematic of the fabrication of BSGs [9]. The two shutters can collimate the ion beam emitted from the linear ion source and adjust the width of ion beam spot (see Fig. 1) projected on the workpiece or BSG substrate. The workpiece mounted on a workbench spins about its center normal line and moves in the transverse horizontal direction in accompany with the workbench. That means the ion beam having an elongated rectangular footprint can scan over the workpiece along the arbitrary direction on the workpiece surface.

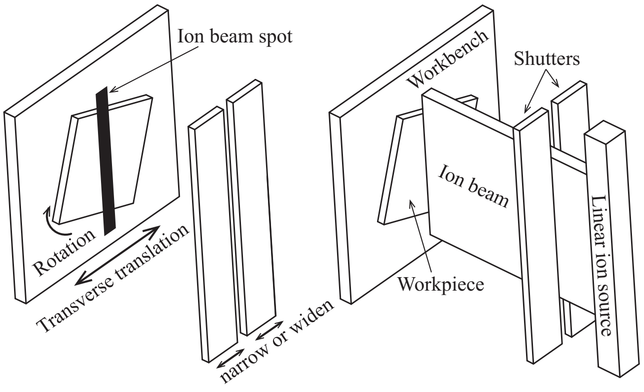

Fig. 1. Schematic of optical fabrication with linear ion source.

As is illustrated by Eq. (3), a series of nonnegative sinusoidal wave surfaces with 1-D profiles linearly buid up a superposed complex surface. So we fabricate the 1-D sinusoidal wave surfaces sequentially instead of fabricating the desired complex suface in one shot. The device shown in Fig. 1 is desined for making the superposition of 1-D optical surfacing process easier to operate. In additional, we have compared two approaches in our previous work [10] to calculate the dwell time distribution in corresponding with a sinusoidal profile.

4. Applications

4.1. Fabrication of large-aperture BSGs

Recently we fabricated large-aperture BSGs by reactive ion etching (RIE), where the ion beam emitted from linear ion source scans over BSGs along a linear guide meanwhile the rotary leaf scans along the elongated footprint of ion beam, thus the spatial

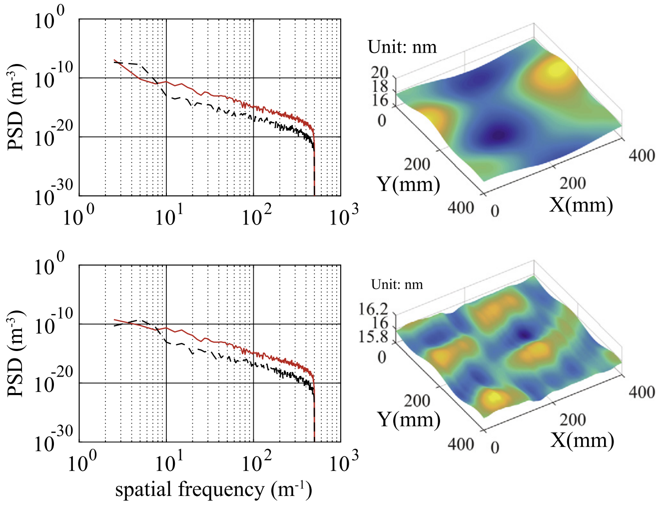

Fig. 2. Surface decomposition based on PSD analysis. The upper shows the desired etch depth map and its PSD plots along coordinate X (solid curve) and coordinate Y (dotted curve); the lower shows the etch depth residuals obtained by removing S_1 (see Fig. 3) from the etch depth map.