A Linnik Scanning White-Light Interferometry System using a MEMS Digital-to-Analog Converter

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Abstract

In this work, we develop a scanning white-light interferometry (SWLI) system which uses a micromechanical digital-to-analog converter mirror module (M-DACMM) to introduce precise nano-scale phase steps. The M-DACMM converts a 4-bit digital signal to a mechanical out-of-plane displacement that is proportional to the analog value represented by the 4-bit binary code. A fabrication process is proposed to realize a large-area movable mirror without release holes. The measured full-scale displacement of the M-DACMM is 1050 nm, and the motion step is 72 nm, which is well suited for the SWLI system. The measurement results using the SWLI system, which phase steps are realized by the M-DACMM, is also demonstrated.

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Keywords: white-light interferometry; micromirror; micro-electro-mechanical systems (MEMS); digital-to-analog converter (DAC)

1. Introduction

The scanning white-light interferometry (SWLI) has been widely used in industries for fast and accurate surface-profiling measurement [1],[2]. In a SWLI system, the measurement is based on the analysis of the interferograms in multiple phase steps. The phase steps are typically controlled by varying the optical path difference, which can be realized by precisely moving the reference mirror (or the object) using an ultra-high-precision linear actuator with a feedback control module.

Recently, micro-electro-mechanical-systems (MEMS) digital-to-analog converters (M-DAC) have been proposed to generate discretized mechanical displacement with simple digital input signals. The M-DAC devices can provide highly repeatable and accurate displacement without the need of feedback control systems. In [3] and [4], surface-micromachined M-DAC devices were proposed to actuate a movable platform in out-of-plane motion for the potential applications in tunable cavity diode lasers or variable optical attenuators.

In this work, we develop a SWLI system which uses an M-DAC mirror module (M-DACMM) as a reference mirror with precise phase step motion. The M-DACMM, which consists of a mirror, a digital-to-analog converter and 8 electrostatic parallel-plate actuators, can be monolithically fabricated by using micromachining techniques. Also, a fabrication process is proposed for realizing a large-area mirror (1mm in diameter) without release holes.

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doi:10.1016/j.proeng.2010.09.219
The M-DACMM device has advantages of high position accuracy, high repeatability, and small size. Also, the device can be easily controlled by simple actuation circuit, which further reduces the cost of the SWLI system.

2. Design and system configuration

Fig. 1(a) shows the schematic of the proposed SWLI system. A tungsten-halogen lamp serves as the light source. The beam-splitter (BS) divides the light beam into an object beam and a reference beam. The reference beam and the object beam are focused onto a reference mirror and a test surface, respectively. After reflection, the two beams recombine and produce an interferometric pattern, which can be captured by a CCD camera. Interferograms of different phases are obtained by moving the reference mirror which is realized by the proposed M-DACMM device. After analyzing the interferograms of different phases by seven-point algorithm [5] and fringe-order identification method [6], the surface profile of the test sample can be evaluated.

![Fig. 1. (a) The schematic of the optical surface profiling system, (b) the picture of the optical surface profiling system, and (c) the picture of the assembled M-DACMM device.](image)

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Fig. 2 shows the schematic of the proposed 4-bit M-DACMM device. This device consists of an out-of-plane movable mirror platform, 4 pairs of parallel-plate capacitive microactuators, 4 pairs of connection springs, and 2 pairs of platform suspensions, as shown in Fig. 2(a). Fig. 2(b) shows the schematic of the electrostatic parallel-plate actuator, which composes of a movable electrode and a fixed electrode. The movable electrode is supported by four electrode suspensions. With zero applied voltage between the two electrodes, the gap between the two electrodes is \( g \), and the actuator is at the suspended state. As the applied voltage is greater than the pull-in voltage, the movable electrode is pulled down onto the dimples, and the actuator is at the contact state. Note that the dimples are used to avoid direct contact between the movable electrode and the fixed electrode.

![Fig. 2. The schematic of the M-DACMM device: (a) the 4-bit M-DACMM structure and (b) the electrostatic parallel-plate actuator. Note that one quarter of the movable electrode is removed for exposing the fixed electrode and dimples.](image)

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The spring constants of these springs are specially designed so that the displacement of movable platform is discretized based on the input control codes. An analog output can be generated by the combination of the bits actuated by the parallel-plate actuators. The displacement of the mirror platform in the N-bit device is given by [3]:

\[
x = \frac{(2^N - 1)k \cdot g}{k + (2^N - 1)k} \cdot \frac{1}{2^N - 1} \sum_{i=1}^{2^N} b_i
\]

(1)

where \( k, 2k, ..., 2^N k \) are the spring constants of the connection springs between the mirror platform and the parallel-plate actuators, and \( k_p \) is the spring constant of the platform suspension. The gap spacing \( g \) is the actuator’s displacement once it is actuated. \( b_i \) is the binary control bit (0 is at suspended state, and 1 is at contact state), and \( i = 1, 2, ..., N \).
Table 1. The design parameters of the connection springs.

| Connection springs | Bit1 | Bit2 | Bit3 | Bit4 |
|--------------------|------|------|------|------|
| Primary meander length (a) (μm) | 70   | 70   | 70   | 70   |
| Secondary meander length (b) (μm) | 500  | 454  | 454  | 494  |
| Number of periods (n) | 10   | 8    | 6    | 4    |
| Spring constant (K) (N/m) | 0.2462 | 0.4918 | 0.9878 | 1.9711 |

For the connection springs, a meandering spring design is employed. The meandering spring constant in the out-of-plane direction can be estimated as [7]:

$$K = \frac{8n^2a^2 + 2nb^2}{3EI_a} + \frac{abn[3b + (2n+1)(4n+1)]}{3GJ} - \frac{n^2a^2 + (2n+1)b^2}{2EI_a + b} \left( \frac{a}{GJ} + \frac{b}{EI} \right)^{-1}$$

(2)

where the structure thickness t is 10 μm, the beam width w is 30 μm, Young’s modulus E is 130.1 GPa, the shear modulus G is 79.9 GPa, the moment of inertia I is wr/12, and the torsion constant J is 0.263wr². The design parameters for the connection springs are shown in table 1. Note that the platform suspensions k_p are designed to be the same as the connection spring for Bit3. Finally, the displacement of the platform can be obtained from (1):

$$x = \frac{G}{2\beta} \sum_{i=1}^{2^N} x_i$$

(3)

For the seven-point algorithm, each motion step of the reference mirror is λ_0/8, where λ_0 is the mean wavelength emitted by the light source. From (3), the gap spacing g should be 23λ_0/8.

3. Fabrication and assembly

Fig. 3 shows the fabrication process of the M-DACMM device. The device is composed of a platform layer and an electrode layer. For the platform layer, the starting material is a silicon-oxide-insulator (SOI) wafer (Fig. 3(a)). The backside release hole, which will be used for releasing movable mirror, is etched by KOH anisotropic etching (Fig. 3(b)-(c)). Then, the mirror platform, connection springs and actuators are patterned and etched by DRIE etching (Fig. 3(d)-(e)), and are released by using hydrofluoric acid (Fig. 3(f)). Finally, a thin gold layer of 1000 Å is deposited on the mirror platform for improving the reflectivity (Fig. 3(g)).

For the electrode layer, the glass substrate (Pyrex 7740®) is etched in HF/HCl [8] to form a gap spacing by using photoresist as etching mask (Fig. 3(h)-(i)). The dimples are formed by further etching with HF/HCl (Fig. 3(j)). Then, the Cr/Au is deposited and patterned as the fixed electrodes (Fig. 3(k)). Finally, the platform layer is assembled to the electrode layer (Fig. 3(l)). Fig. 4 shows the SEM pictures of the platform layer and the electrode layer. The fabricated devices were assembled and wire-bonded on a PCB for testing, as shown in Fig. 1(c).
4. Measurement and discussion

The displacement of the mirror platform with respect to different digital control codes is measured by a laser Doppler vibrometer. For the contact state, a driving voltage of 60 V is applied to ensure the movable electrode fully contacts the dimples on the fixed electrode. Fig. 5(a) shows the transient behaviors of the platform with the actuations of different input bits. Fig. 5(b) shows the measured displacement of the 4-bit M-DACMM device as a function of input control codes. It is observed that the displacement increases linearly with the input binary code. The measured full-scale displacement is 1050 nm, and the motion step (the least significant bit, LSB) is 72 nm. Since the mean wavelength emitted by the tungsten-halogen lamp of the measurement system is about 570 nm, the motion step, which corresponds to $\lambda / 8$, is well suited for the applications of SWLI.

![Fig. 5. (a) the transient behaviors of the mirror platform and (b) the analytical and measured displacements of the M-DACMM device.](image)

The picture of the proposed SWLI system is shown in Fig. 1(b). The closer view shows the M-DACMM device which serves as the reference mirror. Fig. 6(a) shows the measured shape of a grating structure which was fabricated by etching a silicon substrate with RIE. During the measuring process, the input binary codes “0000” to “0110” are applied to the M-DACMM device in sequence, and the images of different phases are acquired. By analyzing the images using the seven-point algorithm, the surface profile is obtained. Compared with the results measured by a stylus profilometer, the average discrepancy is within 10 nm, as shown in Fig. 6(b).

![Fig. 6. The measured results of the grating structure: (a) the 3D profile and (b) the line profile of the sample across the grating structure.](image)

5. Conclusions

In this work, a SWLI system, which uses an M-DACMM for serving as a reference mirror with precise phase motion step, is developed. The M-DACMM generates out-of-plane mirror displacements which are proportional to input 4-bit digital signals. To realize a large-area movable mirror without release holes, a micromachining fabrication process is proposed. The proposed M-DACMM has advantages of high position accuracy, high repeatability, and small volume. Also, it is controlled easily without sophisticate control module, and further reduces the cost of the SWLI system. The measurement results using the SWLI system are also demonstrated.

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