RHOMBIC-SHAPED THERMAL ACTUATOR ARRAY FOR EVENLY-DISTRIBUTED VERY LARGE DISPLACEMENT

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ABSTRACT

This paper presents a design of thermal actuator array to generate evenly-distributed displacement by cascading an array of rhombic-shaped units. Such design is implemented to a tunable grating to tune the period by 61% and to produce a total displacement of 215 µm. Such design is scalable to the sub-wavelength level, making its very attractive to many tunable nano-photonic devices.

1. INTRODUCTION

Microelectromechanical systems (MEMS) technology utilizes the photolithographic processes to fabricate movable mechanical structures in the micrometer level [1, 2]. Compared with the conventionally bulky counterparts, the MEMS devices have shown drastic improvement of performance such as small size, fast response speed, large tuning range and better mechanical stability. Actuators are essential to MEMS devices to generate the force, which makes the movement possible. Compared with the widely-used electrostatic actuators such as the comb drives and the parallel-plate capacitor actuators [1, 3, 4], the thermal actuators are able to produce large displacement and large force in a compact footprint [1, 5-8].

Thermal actuators make use of the small amount of thermal expansion and have specially designed structures to amplify such expansion. They mainly come into two configurations, the bimorph and the V-shaped. There are many other variants of designs, but these two are the basic types. The first has two asymmetrical arms arranged in parallel, one has long expansion while the other has short expansion under the same driving current [5-7]. A single actuator is able to generate large displacement but weak force. A V-shaped actuator has two symmetrical arms joined at an obtuse angle as shown in Fig. 1(a). The small expansion of the arms can push out the vertex [5, 8]. It can produce large force but limited movement (< 10 µm).

On the other hand, tunable gratings are basic components for optical systems such as spectrometers, tunable lasers and laser scanners etc [9-13]. Especially the subwavelength gratings have found many applications in nano-photonic systems [14]. Various MEMS designs have been applied to the tunable gratings [11-13], but very few of them are able to tune the grating period by a large ratio. A recently breakthrough made use of the soft electroactive polymer as the grating material, which provided 32% of period change [15, 16]. Besides, the tuning of grating period requires the actuator to provide an evenly-distributed displacement to move the grating lines at the same amount relative to the neighboring lines. None of the existing actuators has such function.

This paper aims at developing a thermal actuator that produces evenly-distributed displacement to obtain large tuning ratio of the period. This paper will present the concept and designs in Section 2, followed by the experimental results in Section 3.

2. DEVICE DESIGN

2.1. Rhombic-shaped thermal actuator

The working principle of the basic V-shaped thermal actuator is shown in Fig. 1(a). The two identical arms are anchored to the substrate at the end. When a current flows through the arms, the joule heat would cause the arms to heat up by \( \Delta T \). As a result, each arm is extended. Since the two arms are anchored, the joint point of the two arms has to move forward by \( \Delta d \) as given by

\[
\Delta d = \sqrt{d_0^2 + 2l_0 \Delta T - d_0^2} - d_0
\]

where \( d_0 \) is the initial vertical position of the joint point, \( l_0 \) the initial length of the actuator arm, \( \Delta T \) the

Figure 1: The basic V-shaped thermal actuator. (a) Working principle; and (b) actuation relationship.

\[\text{Estimated by Eq. (1)}\]

\[\text{Estimated by Eq. (2)}\]
extension of the arm, and $\alpha$ the thermal expansion coefficient ($2.6 \times 10^{-6}$/C for the single crystalline silicon at the room temperature). In case of small temperature change, it has $2l_0\Delta d + \Delta d^2 \ll d_0^2$, therefore the expression can be simplified to be

$$\Delta d = \frac{i d_0}{l_0} \Delta l \quad (2)$$

Since commonly $l_0 \gg d_0$, a small extension of the arm can lead to a large shift of the joint point thanks to the magnification ratio $l_0/d_0$. To give an idea of the actual amount of movement, the extension of the arms and the actuator movement are plotted relative to the temperature change as shown in Fig. 1(b). The parameters will be given in the next subsection. With a temperature increase of 250 K, each actuator arm is extended by only 0.1 µm, however the displacement of the vertex can reach 3.2 µm as estimated by Eq. (1). It proves that significant movement can be obtained even though the arms’ extension is very small. From Fig. 1(b) it also shows that Eq. (2) tends to overestimate the shift. For example, at a temperature increase of 150 K, the values given by Eqs. (1) and (2) are 2.2 µm and 2.9 µm, respectively. It is overestimated by 32%.

Figure 2: Conceptual design of the rhombic-shaped thermal actuator. (a) The initial state; and (b) after heating up.

Figure 3: Formation of the tunable grating that makes use of the rhombic-shaped actuator array.

The V-shaped thermal actuator itself cannot be cascaded to produce large displacement. To solve this problem, two V-shaped actuators are used to form a rhombic-shaped unit $ABCD$ as shown in Fig. 2(a). In addition, a diagonal beam $CD$ is added. When a driving current is applied between the points $A$ and $B$, it flows through the four arms and causes extension as shown in Fig. 2(b). Nevertheless, no current passes through the beam $CD$ since the points $C$ and $D$ are at the same potential level. Therefore, the beam $CD$ does not extend. This is one of the key features of this actuator. When the current $i$ flows through each side of the arms, each of the V-shaped part produces a movement of $\Delta d$, and in total the point $B$ is shifted by $2\Delta d$ to the point $B'$. Since the current flows from $B$ to $A$, such rhombic-shaped unit can be easily cascaded to produce large displacement.

2.2. Designs of the tunable grating and the rhombic unit

The grating requires displacing many grating lines at the same time so as to change the grating period uniformly. The cascading of the rhombic-shaped actuator units well meets the requirement as shown in Fig. 3. Each grating line is supported by two actuator units at its two ends, while the actuator units are cascaded. When the driving current is applied, each actuator unit will be expanded by the same amount and thus the gap of grating lines will be increased evenly. As a result, the grating period will be tuned.

However, the designs in Figs. 2 and 3 cannot be fabricated directly. The MEMS fabrication has always limit accuracy (typically 0.25 µm) and certain requirement for the minimum space and minimum feature size (both typically 2 µm). For this reason, the sharp angle $\angle BCD$ in Fig. 2 may have to be rounded after fabrication, and the same problem for the connecting part between two actuator units in Fig. 3. To circumvent this problem, the arms are shifted apart by $d_2$ with some blocks added to the arm ends as shown in Fig. 4(a). The parameters are $w = 3$ µm, $d_0 = 3$ µm, $L = 150$ µm.
(i.e., \( b_0 = 150.03 \mu m \), \( a_1 = 3 \mu m \), \( a_2 = 3 \mu m \), \( b_1 = 12 \mu m \), and \( b_2 = 6.5 \mu m \) as defined in Fig. 4(a)).

In the design, the grating line has a width of 4 \( \mu m \) and is separated by 3 \( \mu m \). As a result, it has \( p_0 = 7 \mu m \). According to Fig. 1(b), the grating period will be 11.4 \( \mu m \) at \( \Delta T = 150 \) K. As estimation, the grating period will be tuned as high as 63%. The number of grating lines is \( N = 50 \).

To solve the problem, the connection part between each grating line and the actuator units are folded as shown in Fig. 4(b). In this way, it enables small initially grating period and thus large tuning ratio. The grating period \( p \) is given by \( p = p_0 + 2\Delta d \), where \( p_0 \) is the initial grating period.

However, the introduction of the blocks makes the actuator arms have large size in the vertical direction and thus has large grating period of \( 2(a_1+a_2+d_0)+w = 21 \mu m \) if the grating lines are directly attached to the actuator units. To solve the problem, the connection part between each grating line and the actuator units are folded as shown in Fig. 4(b). In this way, it enables small initially grating period and thus large tuning ratio. The grating period \( p \) is given by \( p = p_0 + 2\Delta d \), where \( p_0 \) is the initial grating period.

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The scanning electron micrographs (SEMs) of the tunable grating and its close-up are shown in Fig. 5(a) and (b), respectively. The MEMS structures are fabricated by the deep reactive ion etching on the 8” silicon-on-insulator wafer (structural layer 75 \( \mu m \) thick). The movable parts are released by the dry method [17]. As the resistivity of the single crystalline silicon is quite high, the actuator array measures a resistance of > 2 M\( \Omega \), which needs > 40,000 volt to generate a current of 20 mA, too large to be practical. Metal coating should be applied to reduce the resistance. Gold is not ideal due to its very low resistivity, which in turn requires high driving current. To solve this problem, the MEMS part is uniformly coated with a layer of titanium (0.3 \( \mu m \)). In the grating line part, one more layer of gold (0.2 \( \mu m \)) is coated to increase the grating reflectivity. Finally, the actuator array has a resistance of 5 \( \Omega \) - 10 k\( \Omega \).

The states of the actuator units are captured using a charge-coupled device (CCD) camera under a microscope. The initial state is shown in Fig. 6(a). It has 9 units of the actuators in the observation window. When the current is increased to 8 mA, the actuator units start to move slightly as shown in Fig. 6(b), part of the 9th actuator unit is shifted out of the window. At higher current of 14 mA, further movement is generated as shown in Fig. 6(c). Only 8 actuator units are left in the same window. The relationship between the movement of each actuator unit and the driving current is shown in Fig. 7.
current is plotted in Fig. 7. When the driving current is below 6 mA, no significant movement can be observed. Then the movement goes up to 4.3 µm when the current is increased to 27 mA (ΔT ≈ 150 K according to Fig. 1(b)). Further increase of the current causes a slow reduction of the movement. A linear relationship is well maintained over the whole movable range following \( y = 0.21x - 1.42 \), where \( y \) is the movement in µm and \( x \) is the current in mA.

When no current is applied, the +1st diffraction order of the normal incidence is at 12.8°. The diffraction spots captured by the infrared CCD camera are shown in Fig. 8. At a fixed angle position, the diffracted light would have different wavelength when the grating period is tuned. The spectral shift of the +1st order is shown in Fig. 9. It obtains a shift of central wavelength by 13.4 nm when the current is changed from 0 to 10 mA. Theoretically, the wavelength can be changed by 1 µm for a temperature change of 150 K.

CONCLUSIONS

This paper presents a design of thermal actuator array to generate evenly-distributed displacement up to 215 µm, and also demonstrates its application to the tunable grating, whose period is tuned by 61%. Compared with the other actuators, this array processes the advantages of very large displacement, symmetric design and large force, and would find applications in tunable MEMS devices.

REFERENCES