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Improved Design of Polymeric Composite Electrothermal Micro-Actuator for High Track Density Hard Disk Drives

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ABSTRACT

Recently, we have developed a polymeric composite electrothermal micro-actuator for dual-stage applications in hard disk drives (HDDs). The polymer composite was demonstrated with a larger thermal expansion as compared to silicon. Yet, the previous design of polymeric composite thermal actuator was stiff, having a high mechanical resonant frequency at 33 kHz and a moderate static displacement stroke of 50nm at 4V. An even larger stroke above 100nm is generally required to meet the need of HDD dual-stage systems. To meet the requirement for a large stroke, we presented an improved design of polymeric composite electrothermal micro-actuator by increasing flexibility of the composite thermal benders. As compared to the previous design, the new design doubled the displacement stroke up to 106 nm at 4V while it maintained a high mechanical resonant frequency of 31 kHz, slightly below that of the previous design. In addition, a finite element analysis showed that electrothermal activation of the micro-actuator is rather localized and it causes only a small temperature rise of the neighbouring parts of head gimbal assembly (HGA). These good performances suggested that this improved design of thermal micro-actuator is promising for high bandwidth dual-stage positioning systems in future high track density HDDs.

Keywords: MEMS, Thermal micro-actuator, Hard disk drive, Dual-stage positioning

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1. Introduction

As the recording density of hard disk drive (HDD) is continuously increasing, more accurate and much fast head positioning servo mechanical systems are required (Wood et al. 2002). When the density is approaching to 4 Tb/in^2, magnetic recording media need to accommodate 1000k tracks per inch (TPI) at the least. In such high track density, a track size of 25 nm wide can only allow the track misregistration (TMR) to be 2.5nm (3σ) approximately. However, a dual-stage PZT based milliactuator is very difficult to support such high track density. Its servo bandwidth is limited to about 3 kHz mainly by the suspension's primary resonance modes (Numasato and Tomizuka 2003). This had led to the development of various slider-level and head-level dual-stage positioning schemes to increase HDD servo bandwidth for lowering the sensitivity to disturbances with improved track-following and track-seeking performances (Hirano et al. 1998, Soeno et al. 1999, Kurihara et al. 2004, Hirano and Yang 2005, Toshiyoshi et al. 2002).

Recently, electrothermal micro-actuators at the slider-level and head-level have been proposed and developed as an alternative solution for dual-stage positioning. As compared to piezoelectric and electrostatic micro-actuators, the solid electrothermal micro-actuators are capable of generating a large force at a low driving voltage (<5V) and adequately fast response (>1 kHz) (Choe et al. 2010). In addition, they have a high stiffness and consequently can achieve a high mechanical resonant frequency for precise positioning.

In the electrothermal micro-actuator design, choice of materials is a determining factor to the stroke-generation capability per unit temperature rise. Various thermal expansion materials were used in the slider-level micro-actuators. For example, Choe et al. (2010) developed a thermal micro-actuator using silicon expander to generate a motion less than 2.5nm (static) at +/-3.5V. Messner et al. (2009) and Bain et al. (2010) proposed a rotary thermal micro-actuator using aluminium/silicon-oxide composite expander to rotate less than +/-5 degree (static) by up to 10V. By using a highly expandable polymer composite (SU8/Si), Lau et al. (2012) and Yang et al. (2012) reported a polymeric composite thermal micro-actuator capable of driving a femto slider at a larger stroke of 50nm (static) under 4V. On the other hand, Liu et al. (2012) had made use of solid thermal expansion of alumina to move the read write head up to 7nm (static).

However, the thermal micro-actuators developed so far at the slider or head level generate a small displacement stroke, which may be useful for improving the track-following performance of dual-stage actuation systems. To enable the track-seeking mode such as short-span seeking, a large displacement stroke is desired. Polymer expansion material is particularly good for large expansion (Lau et al. 2007) as compare to the rest. Hence, there is further room to improve the actuation stroke produced by the polymeric composite thermal micro-actuator. In this paper, we are going to show that polymeric composite electrothermal micro-actuator can generate a larger stroke without much compromising the high mechanical resonance frequency, 30 kHz, of the micro-actuator/slider system.

In the subsequent sections of the paper, we shall show the dependence of the induced thermal stroke and the mechanical resonant frequency on a key design parameter, i.e. the silicon beam width of the thermal bender. Parametric analysis leads us to an improved design with a larger stroke and high mechanical resonant frequency. Fabrication and testing of this new design of polymeric composite thermal micro-actuator will be presented to validate improved performances. In addition, finite element simulations are conducted to evaluate whether the activation of the electrothermal micro-actuator will adversely affect its carrier, i.e. a head gimbal assembly (HGA).

2. Design Consideration

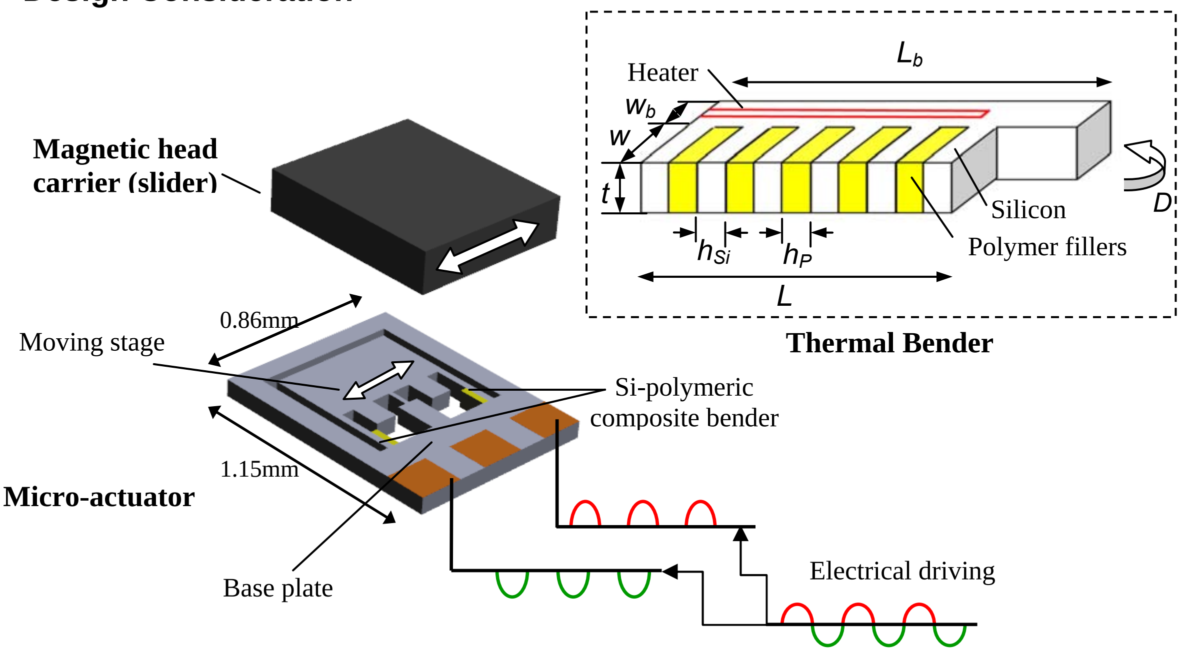


Fig. 1 Schematic of a micro-actuator carrying a magnetic head slider: each of the composite benders is electrothermally activated by a supply of half-sine voltage pulses

The present design of slider-level micro-actuator, as shown in Fig. 1, has a moving stage on the support of three silicon flexural beams, among which two side beams are integrated with thermal benders and a middle beam acts as a pivot. Each thermal bender consists of a comb-shape silicon skeleton and polymer expander (SU8). Upon resistive heating, thermal bender deforms such that the backbone or the beam of the silicon comb bends laterally while polymeric thermal expander pushes open the space between the silicon fins. Under alternate activation of the thermal benders can move the stage, together with a femto slider, into a bi-directional lateral stroke.

As analyzed previously (Yang et al. 2012), geometry design governs the dynamics and actuation performance of the micro-actuator. Stiffening the supporting beams for the moving stage leads to an increase in mechanical resonance frequency. Stiffening the silicon comb backbone of the thermal bender leads to a reduced actuation stroke. The micro-actuator design is however subjected to conflicting requirements, i.e. a large actuation stroke and a high mechanical resonance frequency. As a result, a practical design needs to strike a balance between the two requirements.

Table 1 Design Parameters

	Previous design (μm) (Yang et al. 2012)	**This work (μm)**
Beam width of backbone for silicon comb (w_b)	25	15-30
Beam length of backbone for silicon comb (L_b)	300	300
Middle beam width (w_c)	20	20
Middle beam length (L_c)	100	100
Silicon fin length (w)	30	30
Silicon fin width (h_{si}) or gap (h_p)	10	10
Silicon micro-structure thickness (t)	60-70	60-70

A few common design parameters do affect stage stiffness and the actuation stroke, namely the width w_b, thickness t and length L_b of the flexural side beam with comb backbone, the fin length w and width h_{si} or gap h_p, the width w_c and length L_c of the middle beam, as listed in Table 1. In this study, we keep w, h_{si}, h_p, L_b, L_c, w_c invariable but change the side beam width w_b and thickness t. A parametric analysis based on finite element simulation reveals that the stage stiffness and the comb stiffness increase with w_b and t. As a result, as shown in Figure 2, the thermally induced stroke (displacement) decreases with w_b but the mechanical resonance frequency increases with w_b. The analysis reveals that mechanical resonance frequency remains generally high (above 28 kHz) for micro-actuator design with a beam width ranging from 15μm to 30μm. The previous design adopted a beam width of 25μm and yields very high mechanical resonance frequency up to 33 kHz, which is far higher than what is needed for most dual-stage micro-actuator and suspension resonance frequency.

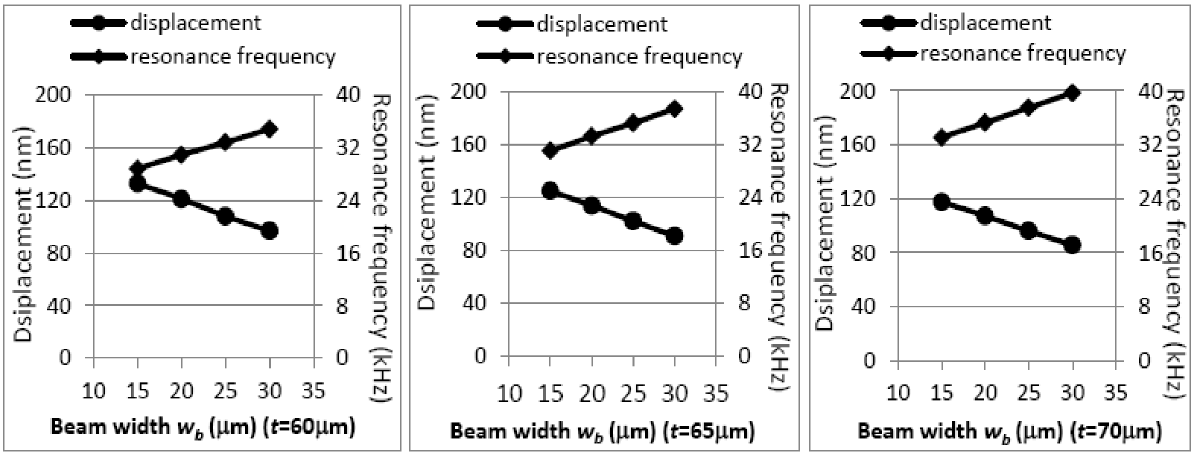


Fig. 2 Simulated displacements and frequencies varying with the beam width

For the sake of increasing the actuation stroke with more than 100nm, the new design needs to adopt a slender beam design with a beam at 15μm or 20μm, which is 40% or 20% smaller than the previous design of 25μm wide. From the figure 2, the slender beam design with 15μm or 20μm beam width increases the actuation up to 23% (132nm), but decreases the mechanical resonance frequency by less than 12%. This analysis suggested that beam width design has larger influence on the actuation than the resonance frequency. This is because the stage stiffness is determined primarily by the middle pivot beam, whereas the actuator stiffness is determined by the width of side beam (i.e. backbone of the comb, which has 30μm long and 10μm side fins). Further analysis of resonance frequencies between the 15μm and 20μm beam width designs indicated the latter can have higher mechanical resonance frequencies above 30 kHz.

In addition, the parametric analysis studied the influence of the beam thickness t, which varies between 60 and 70μm due to micro-fabrication process. Figure 3 show that a thicker beam leads to a slight decrease in the actuation stroke but a slight increase in the mechanical resonance frequency. Despite thickness variation, the overall performance of the micro-actuator is dictated by the beam width. Thus, the analysis suggested that the new design with 20μm beam width is an improved design that can result in an actuation stroke larger than 100nm and a mechanical resonance frequency above 30 kHz.

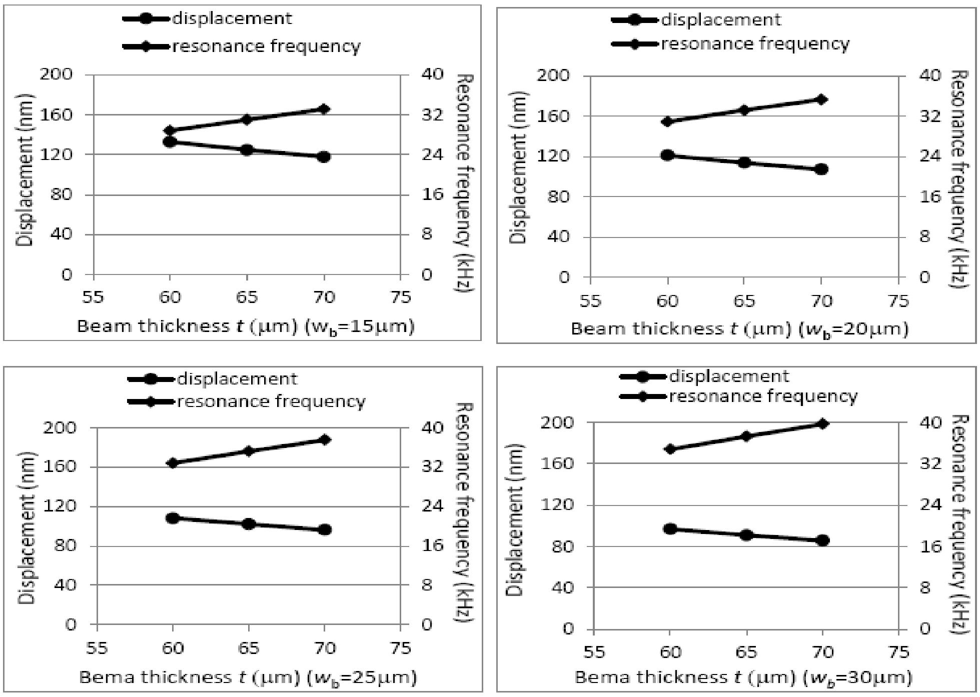


Fig. 3 Simulated displacements and frequencies varying with the beam thickness

3. Experiments

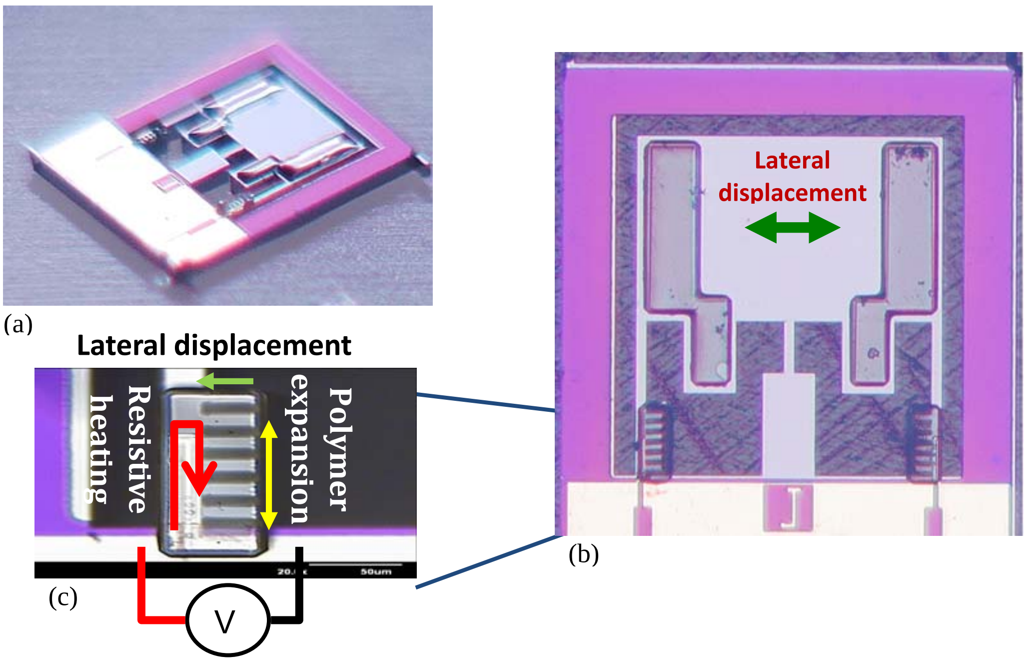


Fig. 4 Micrographs of the electrothermal micro-actuator with enhanced displacement: (a) optical micrograph of the 3D view of the micro-actuator, which consists of a moving stage, two composite benders and a central pivotal beam; (b) optical micrograph of top view of the micro-actuator; (c) close-up optical micrograph of the left composite bender which shows transparent SU-8, silicon comb and a resistance heater.

This new micro-actuator design with a slender side beam (w_b=20μm) was fabricated using the reported fabrication process (Lau et al. 2012, Yang et al. 2012). Figure 4 shows the optical micrographs of a silicon die carrying the thermal micro-actuator. Subsequently, the thermal micro-actuator is mounted adhesively on a printed circuit board, wire bonded to electrical pads, and finally attached adhesively with a femto slider. With this sample preparation done, the micro-actuator on PCB is ready for displacement measurement. Detailed setup of the displacement measurement using laser Doppler vibrometer (LDV) is shown in Figure 5. The setup is placed on a vibration isolation table to avoid the unintended ground noise. During the displacement measurement, laser beam of LDV is shone on the side wall of the femto slider. Two sets of testing were carried out, one to measure a step response by activating a single thermal bender using a square pulse, one to measure bi-directional response by alternately activating two thermal benders using a half-sine pulse.

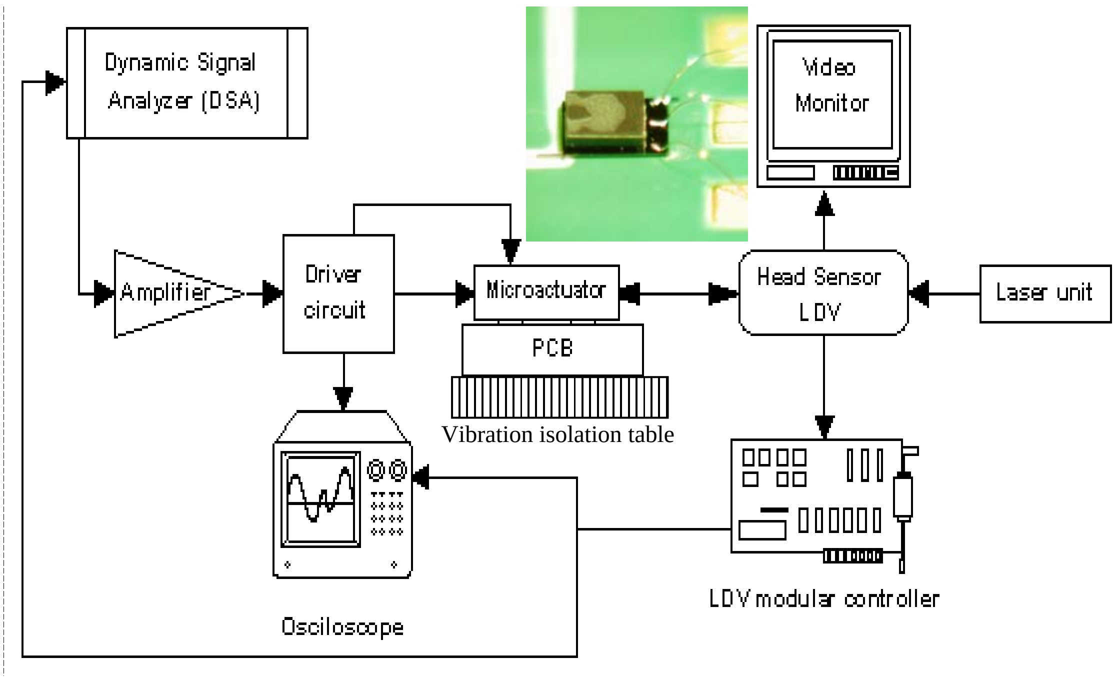
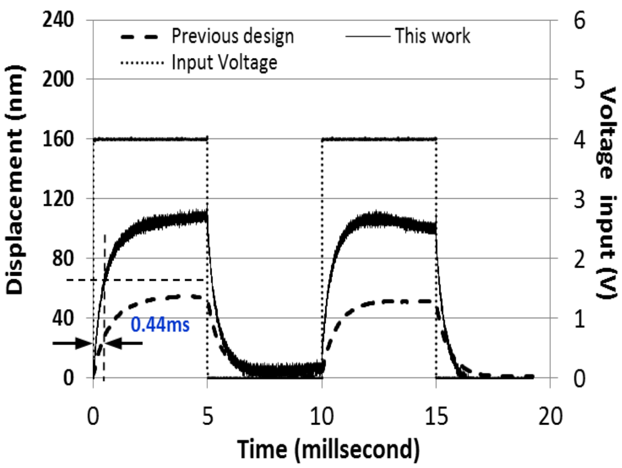


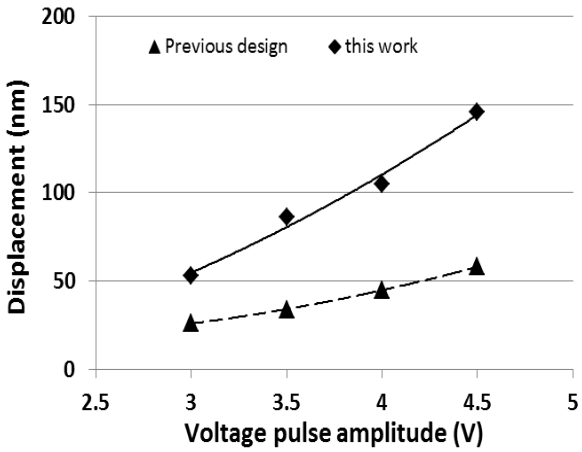
Fig. 5 Experimental setup of the device prototype on the PCB and vibration isolation table with a LDV system and electrical driving circuits

3.1 Step response

Step response of the micro-actuator is measured by activating only one of the two thermal benders using a 4V square voltage pulse with a 5ms pulse width at a 50% duty cycle. Figure 6(a) shows that the slider lateral displacement rises at a decreasing rate like an exponential function of time, when the pulse is on. Within 2ms, the displacement reaches a steady-state value of 106nm that is double of 50nm obtained by the previous design (Yang et al. 2012). Meanwhile, the time constant of the micro-actuator/slider assembly is measured to be 0.44ms, which is 10 % shorter than 0.5ms for the previous design. In addition, the induced steady-state displacement amplitude increases nonlinearly with the voltage amplitude as shown in Figure 6(b). As compared to the previous design, the current design can deliver a larger displacement, ranging between 100-130nm, over the driving voltage range between 3 to 4.5V. The measured 100-130nm displacements are 4-5 times track width of 25nm for 1000k TPI track density. Hence, this new micro-actuator can satisfy the displacement requirement for short-span seeking in the HDD dual-stage systems.



(a)



(b)

Fig.6 Step response under a 4V square voltage pulse input with 5ms pulse width at 50% duty cycle: (a) transient displacement and square voltage pulse over time; (b) steady-state displacement amplitude as a function of voltage pulse amplitude for the present and previous designs

3.2 Bi-directional response

Bi-directional response of the micro-actuator is measured by alternately activating two thermal benders using a half-sine voltage pulse, as shown in Figure 1. During the test, the half-sine voltage pulses are set by the pulse amplitude and driving frequency. Figure 6 shows that bi-directional time response of the micro-actuator under activation at 3.25V pulse at different driving frequencies. It is observed that the peak-to-peak displacement of the micro-actuator changes with the driving frequency. Under the excitation by a 3.25V half-sine voltage pulse at 1 kHz, the micro-actuator delivers a 44m peak-to-peak displacement, as shown in Figure 7(a), whereas it delivers a 10nm peak-to-peak displacement at 5 kHz, as shown in Figure 7(b).

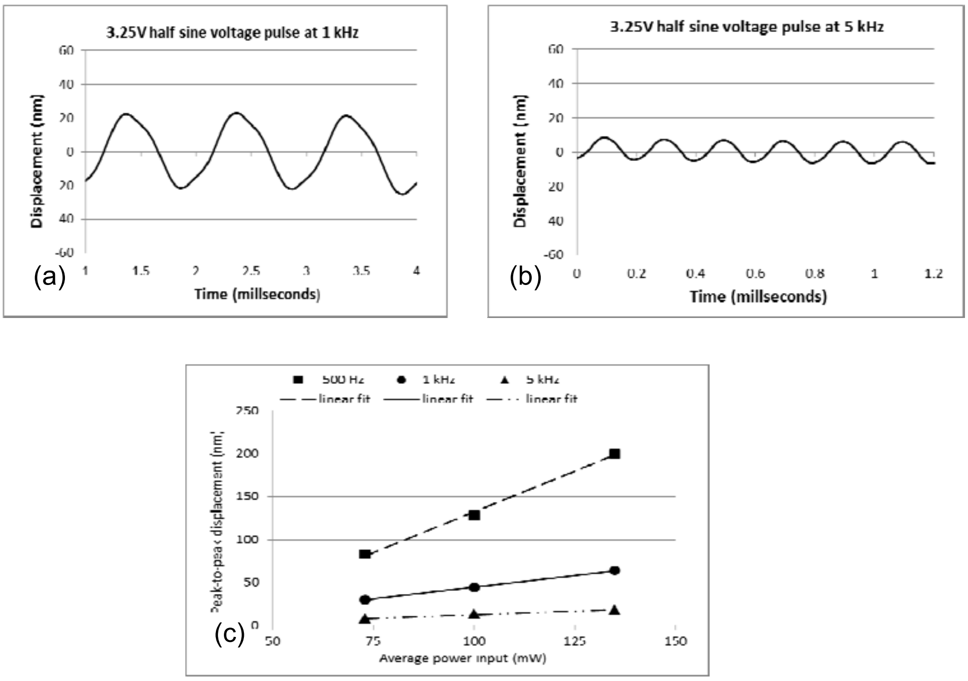


Fig. 7 Bi-directional time response of the slider under the excitation by 3.25V half sine voltage pulse at different driving frequencies: (a) time response under excitation at 1 kHz, (b) time response under excitation at 5 kHz and (c) the peak-to-peak dynamic displacement as a function of average input power at various excitation frequencies

In addition, the peak-to-peak displacement increases linearly with the input power as shown in Figure 7(c). At a constant input power, the induced peak-to-peak displacement decreases with an increase in the driving frequency. This happens because high-frequency pulsed heating leads to more steady-state temperature rise but less dynamic temperature change. Nevertheless, the new micro-actuator delivers a doubled displacement per unit input power as compared to the previous design (Yang et al. 2012). The large dynamic displacements at high frequencies show that the improved design of micro-actuator can meet the precisely track-following requirement for HDD dual-stage systems.

Figure 8 showed the frequency response of the actuated slider, which is obtained by sweeping the driving frequency from 100 Hz to 50 kHz, using a 3.5V half-sine voltage pulse. It is observed that the first in-plane mechanical resonance frequency occurs at 31 kHz, which is slightly lower than 33 kHz in the previous design. In addition, a 3 dB thermal cut-off frequency is identified at about 370Hz. Dual-stage control testing on a head suspension assembly with a voice coil motor showed that this micro-actuator can achieve a high bandwidth of 6 kHz for dual-stage systems in HDDs (Gao et al. 2013).

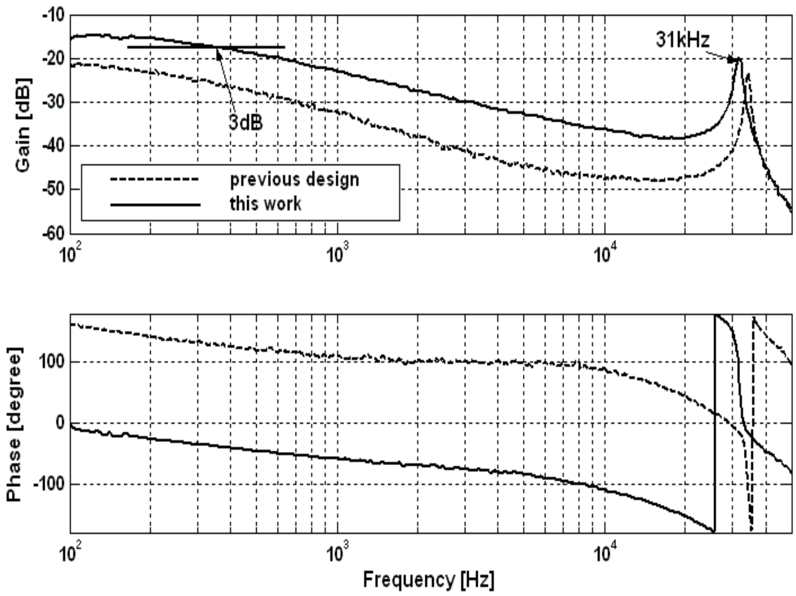


Fig. 8 Frequency response of the micro-actuator with a femto slider attachment

3.3 Performance comparisons

This work showed that a simple design modification using a slender comb beam, which has a width reduced by 20% as compared to the previous design, successfully improves mechanical performance of the micro-actuator. As a result, thermal bender greatly improved the actuation stroke but the slider/micro-actuator system slightly reduces in the mechanical resonance frequency. Performances of the new design and the previous design are compared in Table 2. The improved design has doubled the stroke generation at the same voltage pulse, while it reduces a slightly in terms of the thermal mechanical time constant and mechanical resonance frequency.

Table 2 Comparison of Measured Performances

Experimental Performance	**Previous Design (w_b =25μm)**	**This work (w_b =20μm)**
Steady-state displacement by 4V square pulse	50nm	106 nm
Time constant	0.5 ms	0.44 ms
Peak-to-peak displacement by 3.25V sine pulse at 1kHz	20 nm	44 nm
Resonance frequency (with a slider)	33 kHz	31 kHz

4. Thermal Simulation

Experiments showed that the proposed thermal micro-actuator consumed substantial input power during operation. For example, the micro-actuator under alternate activation by a 3.25V half-sine voltage pulse at 1 kHz consumed 100mW power to generate a 44nm peak-to-peak displacement. As a result of high input power, there was concern if activation of the thermal micro-actuator will cause unintended heating when integrated with HGA. It is not sure if electro-thermal activation of the micro-actuator may interfere with thermal fly height control at the slider tip.

To clarify this thermal issue, a thermal simulation is conducted using a full finite element model, which consists of the thermal micro-actuator and a slider on a HGA, as shown in Figure 9(a). In the simulation, the micro-actuator was loaded such that the two thermal benders were alternately activated by a 4V half-sine voltage pulse at a driving frequency of 1 kHz. On the other hand, the thermal boundary conditions are set such that the air-bearing surface of the flying slider has a heat convective coefficient of 40×10^3 W/m^{2}K, in comparison to 50 W/m^{2}K at other part of surfaces (Juang and Bogy 2007). Other thermophysical properties are assumed temperature independent up to 200°C.

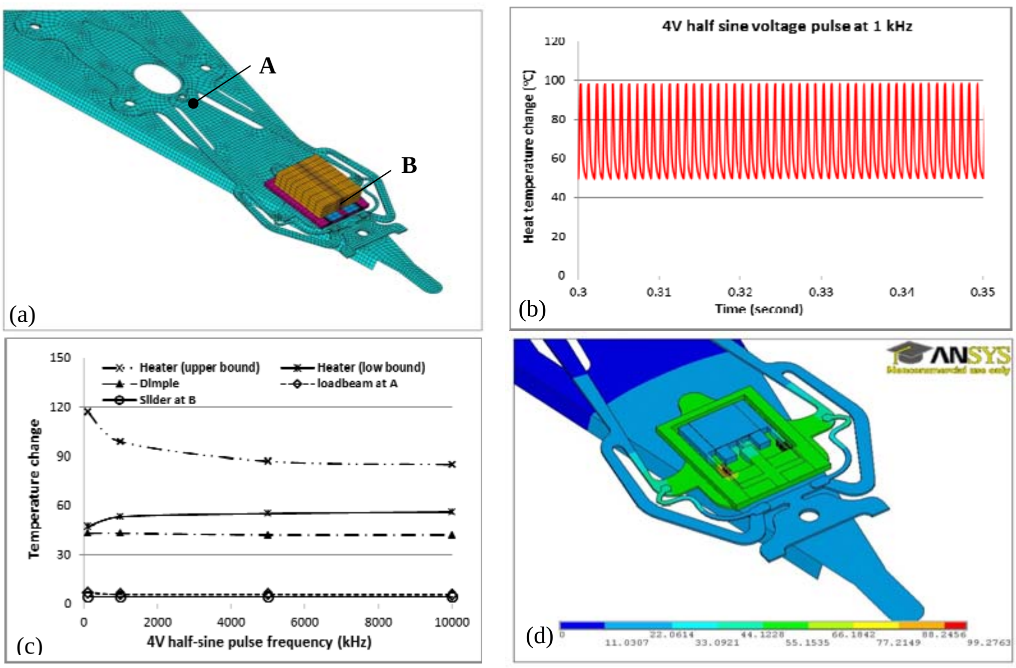


Fig. 9 Thermal simulation: (a) finite element model; (b) heat temperature responses by 4V half sine voltage pulse at 1 kHz; (c) transient temperature responses as a function of driving voltage frequency; (d) temperature distributions by 4V half sine voltage pulse at 1 kHz

Simulation results showed that the temperatures rise and fall following the 4V pulsed heating at 1 kHz. For example, the heater temperature rises and falls between 52°C and 100°C, as shown in Figure 9(b). While the micro-actuator is activated, neighbouring parts such as dimple, slider and the suspension were also affected by the heat. At the steady state (after activation for 1.5 seconds), the dimple rise in temperature by 43°C, while the slider tip (point B) rises 4.3°C and the suspension (point A) rises 5.8°C, as shown in Figure 9(c-d). In comparison, heating by thermal fly control at 100mW will causes a temperature rise of 22.3°C at the slider tip, 3°C at the suspension, and 8°C at the dimple. These simulation results at various driving frequencies revealed that activation of the thermal micro-actuator cause localized heating, leading to small temperature rise to the suspension. The results do not suggest the HGA were adversely affected by thermal micro-actuation.

5. Conclusions

This paper has successfully improved design of a polymeric composite electrothermal micro-actuator for a larger displacement generation at the same driving voltage and power. This improved design has a slender beam design for the comb backbone in the thermal bender. Parametric study showed that this design with reduced beam width struck a balance between the conflicting requirements for a larger actuation displacement and a high mechanical resonance frequency. In comparison to the previous design with 20% wider beam, the new design was experimentally measured to deliver a doubled static stroke generation up to 106nm at 4V without much compromised the mechanical resonance frequency (above 30kHz). Yet, the improved design share the same problem as the previous design in that the micro-actuator consumed high input power, as much as 100mW to produce 44nm peak-to-peak displacement. This suggests that the micro-actuator needs to be further optimized for reduced power consumption while maintaining a large stroke generation and a high mechanical resonance frequency.

Acknowledgements

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