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Active-Passive Hybrid Actuators for Tracking and Focusing Motions in Optical Pickup Devices

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***Abstract* - This paper is aimed to propose a piezo-based optical pickup device with passive damping to enhance the capabilities of precision positioning and shock resistance in optical disk drives (ODDs). The proposed piezo-based pickup device can be combined with a first stage large stroke actuator such as existing sled motor or voice coil motor to form a novel dual-stage servo system for the next generation high resolution ODDs. This active-passive hybrid actuator possesses two piezoelectric actuators cooperated together to move a lever beam that bears an objective lens for tracking motion or to contract or extend the lever beam to lift the objective lens upwards and downwards for focusing motion. Moreover, the viscoelastic damping layer is sandwiched between the constraining layer and the piezoelectric bimorph actuator to act a cushioning function to reduce the transmission of shock to the pickup device and dissipate vibration energies from the device. In the paper, piezo-based pickup devices with and without passive damping are fabricated, tested and compared to verify the design of pickup unit. Experiments are carried out to investigate their damping abilities and transmissibilities. Several parameters are studied to evaluate their effects on the characteristics of the piezo-based pickup device. Finally, the closed-loop performances of the piezo-based pickup device are compared with the current voice coil motor optical pickup using the internal model controller.**

Index Terms* - *Optical disk drive, Blu-ray disc, pickup head, piezo-based actuator, active-passive hybrid

I. INTRODUCTION

High definition (HD) videos and HDTV broadcasting become more popular in the entertainment industry. In order to record and play back HD contents, demand for large capacity optical disc format becomes more pressing. Besides, the prevalent trend of optical data storage device is towards smaller size such as small form factor (SFF) drive with increasing larger data storage capacities such as newly emerging media type of Blu-ray (BD) disc. In order to enable optical disk drives (ODDs) used in portable devices such as mobile phones, MP3 players, camcorders and PDAs, it needs to miniaturize the components of ODDs to meet the requirements. An example is that a DataPlay drive (dimension: 52mm×48mm×11mm) with a micro optical pickup unit, which is mounted on a rotary tracking actuator with tilt focus mechanism, enables a 1 GB storage capacity per 32 mm cartridge [1]. In such SFF drive, although the numerical aperture (NA) of the objective lens has been increased to 0.85, it still uses a red laser (650 nm wavelength). And Togashi et al. [2] proposed another (dimension: 53.7×47×4.75 mm^3) SFF BD optical storage system equipped with 0.85 NA objective lens and 450 nm blue-violet laser. It realized a 5-mm-high drive usable with a cartridge disc. The recording density would be up to 1.5 GB/side in a small disc with a diameter of 30 mm.

In the current optical disc drive, dual-stage servo system is formed by integrating a sled motor for coarse track seeking and voice coil motors for fine tracking and focus tuning. To miniaturize the components and develop novel actuators in optical storage systems is a key issue for the success of SFF ODDs. Lee et al. [3] designed a small rotary voice coil motor (VCM) actuator with an effective focusing mechanism and a sufficient bandwidth for SFF ODD based on BD specifications to increase recording capacity. The miniaturized swing arm actuator design for SFF ODDs with using VCM actuators for tracking and focusing motions also can be found in recent research [4]-[5]. Apart from the rotary type of actuator, a linear type of actuator was also studied in [6]-[7] for small-sized ODDs. The linear VCM actuator was designed to meet the requirements of card size optical storage device.

Nevertheless, the success of SFF ODD cannot only base on the scale-down process for the existing components. It still needs to solve several problems such as bandwidth limitation of the actuators, shock resistance, power consumption, and so on. Wu et al. [8] proposed a dual-stage optical servo system by integrating a MEMS positioning device into a conventional VCM actuator. A bidirectional vertical comb-drive actuator and V-beam thermal actuator drove the objective lens for the focusing and tracking motions, respectively. While the bandwidths for the focusing and tracking actuators are high enough, the stroke of focusing motion is not enough to meet the requirement.

Besides, piezoelectric materials exhibit the advantages of high stiffness, high resolution, and broad bandwidth. And their electromechanical effects enable them easy miniaturization with good dynamic characteristics. Their applications can be found in hard disk drives [9] and ODDs [10]-[11]. However, those studies in ODDs did not consider the small form factor design for the next generation ODDs. The standard form factor of the compact mobile ODD is not

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yet determined but the height of the pickup actuator would be one of the most critical issues in the design. Ko et al. [12] proposed a slim-type optical pickup unit with using two parallel PMN-PT bimorphs. The entire dimension of the pickup unit is 16×6×12 mm^3. It has a bobbin part for a lens between two cymbal amplifiers, and flexure hinges are used as a motion guide to decrease the tangential tilt. In order to tackle coupling motions between the focusing and tracking directions, Yang et al. [13] proposed a stroke-amplifying structure enabling the decoupled tracking and focusing motions actuated by four parallel multimorphs. The focusing stroke has been greatly amplified to meet the requirement of Blu-ray specification.

In the BD system, although the increase of densities was realized by employing lasers with shorter wavelengths and objective lenses with a higher numerical aperture for shorter pit lengths and narrower pit widths, the maximum speed of the spinning disc limits data transfer rates. At the current stage, only 8x speed of data transfer rate can be achieved. By comparing with the theoretical limit of 12x speed, the rotational speed for the BD system still has allowable space to be increased. However, several issues need to be addressed, such as the robustness of the servo system, the mechanical stability of the polycarbonate substrate, acoustic noise level, power consumption, etc. The maximum data transfer rate is dictated by the servo characteristics of the current optical drives rather than recording material or disc/substrate characteristics.

In the BD system, in order to increase the transfer rate, it requires high servo bandwidths of tracking and focusing actuators to read data on the tracks as the spindle speed of the disc is increased. In this paper, a piezo-based optical pickup device with passive damping is proposed to enhance the capabilities of precision positioning and shock resistance in optical disk drives. It integrates the active properties of piezoelectric materials with a passive damping mechanism. This active-passive hybrid design actuates a lever beam, which moves the objective lens in the horizontal direction for the tracking motion and in the vertical direction for the focusing motion with displacement stroke amplification. The tracking and focusing motions of the actuator are simulated by finite element modeling with using ANSYS. Several parameters are studied experimentally to evaluate their effects on the characteristics of the piezo-based pickup device. Finally, the closed-loop performances of tracking and focusing motions are compared with the current optical pickup unit while internal model controller (IMC) is used.

II. Optical Pickup Unit with Active-Passive Hybrid Actuator

A. Piezo-Based Optical Pickup Unit with Passive Damping

A new piezo-based optical pickup device with passive damping is designed to enhance the capabilities of precision positioning and shock resistance in ODDs. The proposed novel pickup device can be combined with a first stage larger stroke actuator such as voice coil motor or existing sled motor in ODDs to form a new dual-stage servo system. In the design, the proposed piezo-based pickup device consists of two main portions as shown in Fig. 1. The first portion is that two piezoelectric bimorph actuators function together to provide active precision positioning by applying voltage. They generate forces and bending moments: 1) to move a cymbal lever beam that bears an objective lens in tracking direction; and 2) to contract or extend the cymbal lever beam to lift the objective lens upwards and downwards in the focusing direction. The piezoelectric actuators have not only high resolution and high bandwidth but also low power consumption and light weight. The second portion is the viscoelastic materials (VEM) sandwiched between constraining layers and the piezoelectric bimorph actuators to act as a cushioning function to reduce and dissipate the transmission of shock and vibration energies to the pickup device. These damping layers would reduce the undesired shock and vibration arising from the internal excitations during the drive operation or external shock excitations.

In order to evaluate the geometric damping effect in tackling critical vibration modes such as the tracking and focusing modes, a pattern of triangular constrained layer damping actuator (TCLDA) is fabricated to compare with another pattern of elliptic constrained layer damping actuator (ECLDA) as shown in Fig. 2(a) and 2(b). Besides, the VEM slots at the fixed ends of the actuators as shown in Fig. 2(c) are used to provide an additional cushioning effect as the actuators bend to actuate the objective lens in different directions.

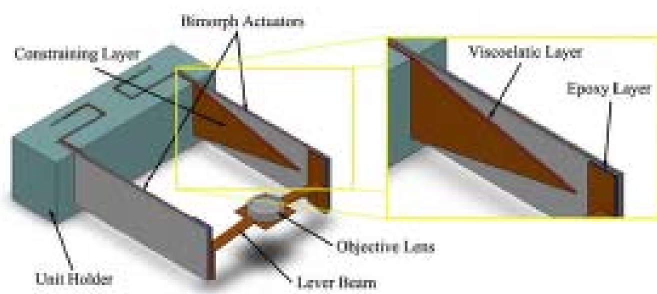


Fig. 1 A piezo-based pickup device with passive damping

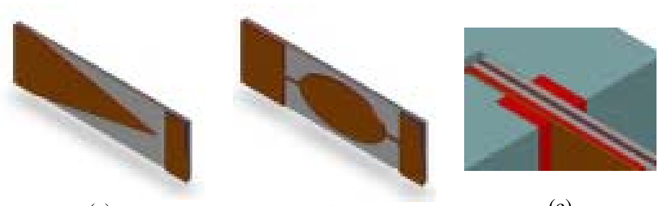


Fig. 2 (a) Triangular constrained layer damping actuator, (b) elliptic constrained layer damping actuator, and (c) VEM slots at the fixed end

B. Finite Element Modeling of Piezo-Based Actuator

Piezoelectrics is the coupling of mechanical and electrical fields, and the piezoelectric material can be modeled in ANSYS using 3-D coupled field solid elements. The whole size of the single PZT-5H bimorph actuator used in the pickup device is 15mm×5mm×0.38mm. A 0.1016 mm brass reinforced shim is bonded between two piezoelectric layers of 0.1392 mm thickness. The piezoelectric matrix is defined in $[e]$ form (piezoelectric stress matrix), which is typically associated with the input of anisotropic elasticity in the form of the stiffness matrix $[c]$. The material constants are given as follows [14]:

$$[c]=\begin{bmatrix} 105 & 56.9 & 59.0 & 0 & 0 & 0 \\ 56.9 & 105 & 59.0 & 0 & 0 & 0 \\ 59.0 & 59.0 & 93.0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 24.1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 21.4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 21.4 \end{bmatrix} GPa, \tag{1}$$

$$[e]=\begin{bmatrix} 0 & 0 & -13.45 \\ 0 & 0 & -13.45 \\ 0 & 0 & 22.70 \\ 0 & 0 & 0 \\ 0 & 5.85 & 0 \\ 5.85 & 0 & 0 \end{bmatrix} C/m^2. \tag{2}$$

And then the density and the relative dielectric constant of PZT-5H are 7800 kg/m^3 and 3800, respectively. The density, modulus of elasticity, and Poisson's ratio of the brass shim are 8530 kg/m^3, 110 GPa, and 0.375. From the simulation, the free deflection and block force of the bimorph tip are 77.2 μm and 101 mN, respectively.

The overall dimension of the pickup head is 15mm×13mm×5mm. Fig. 3 shows the meshed model of the proposed actuator. In the simulation, it aims to check the strokes of the pickup unit under the piezoelectric actuation, the amplification factor of the cymbal lever beam, and the cross effect between the tracking and focusing motions. Therefore, only the brass house, i.e. the constraining layers bonded on the bimorph actuators and fixed on the unit holder is simulated. With the fixed end supports and a combination of tetrahedral, hexahedral, pyramid, and wedge elements used in the meshing of model, there are 62,049 nodes and 22,548 elements used in this analysis. The densities, moduli of elasticity, and Poisson's ratios are 7600 kg/m^3, 99 GPa, and 0.307 for the cymbal lever beam and the house; 16,216 kg/m^3, 411 GPa, and 0.3 for the objective lens; 1,100 kg/m^3, 4.00 GPa, and 0.38 for the epoxy resin, respectively.

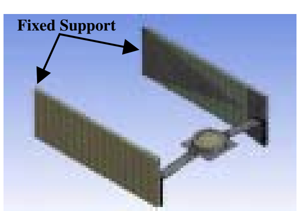


Fig. 3 Finite element model of piezo-based pickup unit

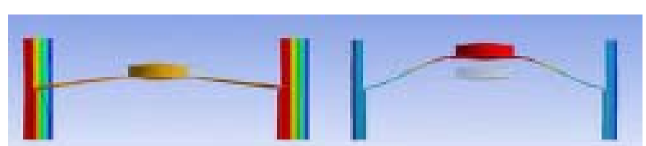
A cymbal lever beam is attached to each bimorph actuator by the epoxy resin in order to support the objective lens [15]-[16]. In the tracking motion, the lever beam is the linkage between two piezoelectric bimorph actuators and supports the objective lens to move leftwards and rightwards. And in the focusing motion, the cymbal lever beam serves as a mechanical transformer for converting and amplifying the small axial strokes of the bimorph actuators into a large focusing stroke. The displacement output of the cymbal lever beam is created by the combination of flexural and rotational motions. The simulation is found that both amplification factors in the TCLDA and ECLDA cases are 8 for the thickness of 0.0508 mm in the constraining layer and the lever beam.

When the bimorph actuators bend in the same direction, the cymbal lever beam as well as the objective lens thereon will be moved towards the tracking direction, as shown in Fig. 4(a). When the actuators bend in opposite directions, for instance, both of the actuators move towards the objective lens, the lever beam will be squeezed and then arched, which in turn lifts up the objective lens. While both of the actuators move far away from the objective lens, the lever beam will be extended, which in turn makes the lens move down, as shown in Fig. 4(b). Under the voltage input of 40 V in the configuration of parallel operation, the tracking and focusing displacement outputs of the TCLDA case are 36.2 μm and 76.8 μm while those of the ECLDA case are 37.3 μm and 81.2 μm, respectively.

In order to analyze the cross effect between the tracking and focusing motions, directional deformations are found as shown in Fig. 5(a)~(d). In the TCLDA and ECLDA cases, for the tracking (Z-direction) motion, the ratios of the focusing motion to the tracking motion at the centre of the objective lens are 1.08% and 1.42% while for the focusing (Y-direction) motion, the ratios of the tracking motion to the focusing motion at the centre of the objective lens are 2.19% and 2.07%, respectively. Therefore, the cross effect between the tracking and focusing motions is not significant for the design.

III. Experimental Results

The prototypes of TCLDA and ECLDA are fabricated and tested as shown in Fig. 6. In the experimental setup, a dynamic signal generator provides the input voltage signal,

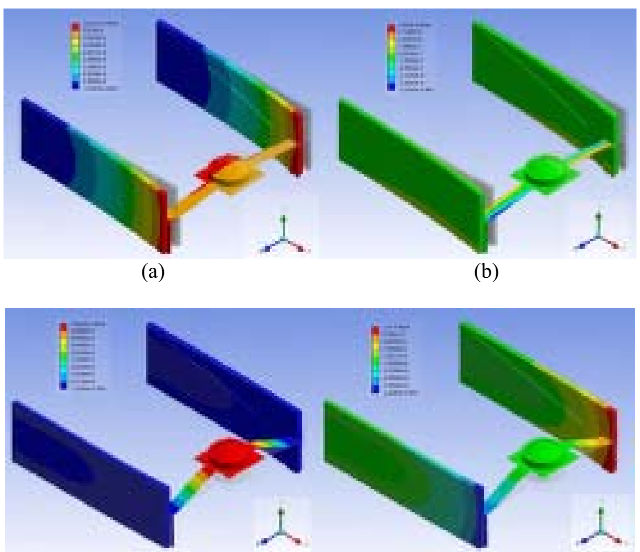


(a) (b)

Fig. 4 (a) Tracking motion, and (b) focusing motion as voltage applied which is powered by an amplifier (AVC 790series) into the piezo-based actuators. The optical laser displacement sensor (Polytec OFV303) measures the displacements of the objective lens of piezo-based actuators and feeds back the signals into the FFT signal analyzer (ONO SOKKI CF-3400). The frequency of the sine wave swept ranges from 5 Hz to 5 kHz. The actuator responses in time and frequency domains due to the swept sine excitation can be obtained.

A. Transmissibility and Bandwidth of Piezo-Based Actuator

Under the voltage input of 80 V in the configuration of series operation, Fig. 7 shows the hysteretic curves for the tracking and focusing motions. The tracking and focusing displacement outputs of the TCLDA case can be up to 53.3 μm and 103 μm while those of the ECLDA case are 58.6 μm and 109 μm, respectively. The strokes in both cases found in the experiment are larger than those in purely active cases (i.e., without VEMs) in the simulation. It is because the VEMs sandwiched between constraining layers and the piezoelectric bimorph actuators would reduce the stiffness of the system while bringing the passive damping to the system.



(a) (b) (c) (d)

Fig. 5 (a) Z-direction tracking deformation, and (b) Y-direction cross focusing deformation while tracking; (c) Y-direction focusing deformation, and (d) Z-direction cross tracking deformation while focusing

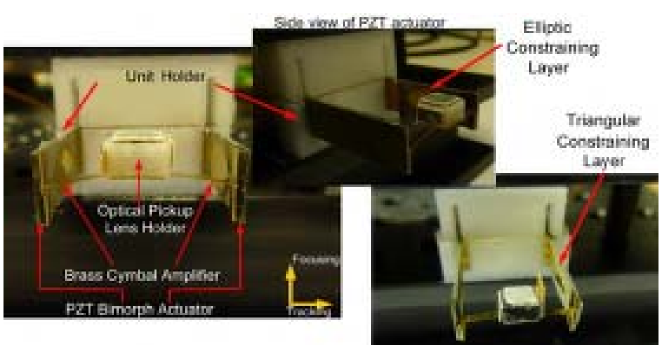


Fig. 6 Fabricated prototypes of the TCLDA and ECLDA cases

Fig. 8 shows the frequency responses of the TCLDA and ECLDA cases in the tracking and focusing motions. Compared with the typical optical pickup actuator designed for BD drive with using VCM actuator [17], the bandwidths of the TCLDA and ECLDA cases have been increased dramatically as shown in Table I. From the simulation for the TCLDA and ECLDA cases in Fig. 9, the estimated 1st mode (focusing) is 318.59 Hz and 305.63 Hz while the estimated 2nd mode (tracking) is 835.95 Hz and 797.9 Hz, respectively.

TABLE I
BANDWIDTH OF FOCUSING AND TRACKING MOTIONS

Bandwidth	VCM	ECLDA	TCLDA
Focusing (Hz)	54	344	275
Tracking (Hz)	57	566	556

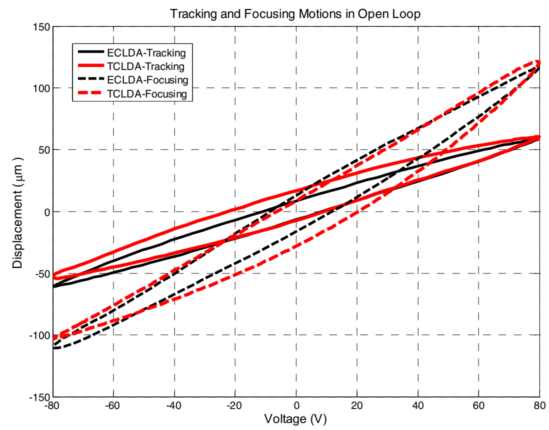


Fig. 7 Displacement outputs of the TCLDA and ECLDA cases under voltage input

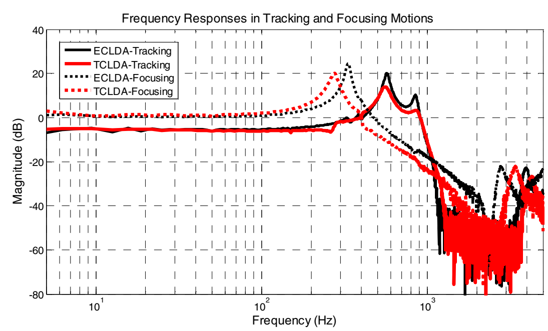
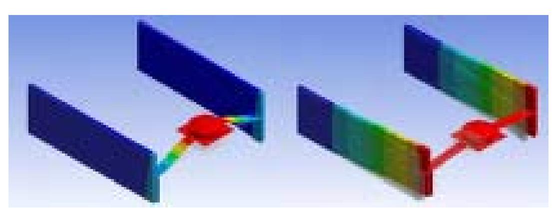


Fig. 8 Frequency responses of the TCLDA and ECLDA cases in tracking and focusing motions



(a) (b)

Fig. 9 Mode shapes of (a) the 1st mode (focusing) and (a) the 2nd mode (tracking)

B. Parametric Study

Tables II and III show the strokes of 80 volt input, bandwidths, and damping ratios of tracking and focusing motions found in different cases. The damping ratio in each case is calculated through the method of half power points. In Table II, comparison of the elliptic constraining layer purely active (ECLPA) and the ECLDA cases shows the addition of VEM constrained layer would reduce the stiffness of the system and increase the stroke of motions. Besides, as the thickness of the constraining and the lever beam decreases from 4 mil to 2 mil, the strokes of motions become larger and more significant increment occurs in the focusing motion, which is increased by 91.2%. The stroke outputs of the configurations of the ECLDA and TCLDA cases are very close.

There is a trade-off between the frequency bandwidth and the damping of a system. In Table III, by comparing the ECLPA and ECLDA cases, the increment in damping would lead to a decrement in the bandwidth of the actuator system. Besides, each slot filled with the damping materials is sandwiched between the sides at the fixed ends of piezoelectric bimorph actuators and the holder. Such type of damping holder is used to provide an additional cushioning effect for the pickup device. The damping ratios of focusing and tracking motions in the ECLDA case without the VEM slots are increased by 8.84% and 15.54% compared with the ECLPA case. For the same thickness of the constraining layer and the lever beam of the ECLDA case with VEM slots, the damping ratios of focusing and tracking motions can be increased up to 32.13% and 18.64%.

The thickness of the constraining layer and the lever beam is also investigated in the study. As the thickness decreases from 4 mil to 2 mil in the ECLDA case with the VEM slots (see Table III), the damping ratio of the focusing motion is increased by 18.24% but that of the tracking motion is reduced by 3.81%. It shows the focusing motion is very sensitive to the change of thickness in the system since the parameter also affects the stiffness of the system especially for the cymbal lever beam. Finally, the VEM damping and constraining layers are specially shaped in order to tackle a critical vibration mode arisen during the device operation. As the shape changes from an ellipse in the ECLDA case to a triangle in the TCLDA case to target the first bending mode, the damping ratios of focusing and tracking motions have been increased greatly by 40.87% and 67.08%. And then it is found that the bandwidth of the system has been decreased from 500 Hz in the ECLPA case to 275 Hz in the TCLDA case for the focusing motion, and from 720 Hz to 556 Hz for the tracking motion. Overall, the TCLDA is better considering stroke, damping and bandwidth. Therefore, only the TCLDA will be implemented and compared with the VCM case in the following experiment.

TABLE II
STROKE OF FOCUSING AND TRACKING MOTIONS

	Displacement (μm)	
	Focusing	Tracking
ECLPA (4 mil*)	36	27
ECLDA (4 mil*)	57	44
ECLDA (2 mil*)	109	59
TCLDA (2 mil*)	103	53

*: Thickness of the constraining layer and the lever beam, separately.

C. Closed-Loop Servo Performances

The experimental setup for testing the closed-loop servo performances is shown in Fig 10. The lens displacement of the pickup device is collected by the laser displacement sensor (Polytec OFV303) and fed back to a DS1104 digital signal processor for implementation of the IMC controller. In the experiment, the sampling time is 10^{-4} sec. The IMC controller is obtained from the IMC tuning of SISO design tool in Matlab with an identified model of the actuator. And then the models of the TCLDA pickup device and the DVD VCM pickup unit are identified through the system identification toolbox in Matlab with the curve fitting technique of the frequency response functions.

The step responses of 100 nm in the tracking and focusing motions for the TCLDA case and the DVD VCM actuator are shown in Figs. 11 and 12. The settling time for tracking and focusing motions to the step change is 2.1 msec and 3 msec in the TCLDA case, respectively, but it seems that the VCM actuator cannot be settled down within the allowable range. Its narrow bandwidth and large stroke make it bounce forward and backward around the destination. As the VCM actuator wants to get close to the target, its low frequency response and large stroke force it across the destination and then the controller will try to get it back on and on. The TCLDA case enables the actuator follow the centre of the track easily. If it gets off the track centre, it will respond quickly to pull the lens back to the track as shown in the zoom figures. The track deviations in the tracking and focusing

TABLE III
BANDWIDTH AND DAMPING OF FOCUSING AND TRACKING MOTIONS

	Bandwidth (Hz)		Damping Ratio	
	Focusing	Tracking	Focusing	Tracking
ECLPA (4 mil*)	500	720	0.0249	0.0354
ECLDA (4 mil*)	450	664	0.0271	0.0409
ECLDA (4 mil* + VEM Slots)	456	656	0.0329	0.0420
ECLDA (2 mil* + VEM Slots)	344	566	0.0389	0.0404
TCLDA (2 mil* + VEM Slots)	275	556	0.0548	0.0675

*: Thickness of the constraining layer and the lever beam, separately.

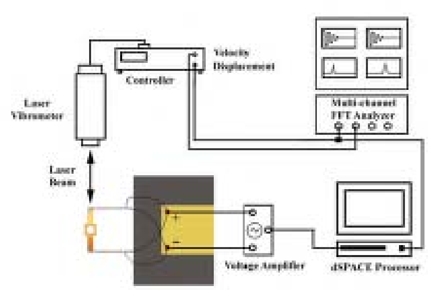


Fig. 10 Experimental setup for testing the closed-loop servo performance

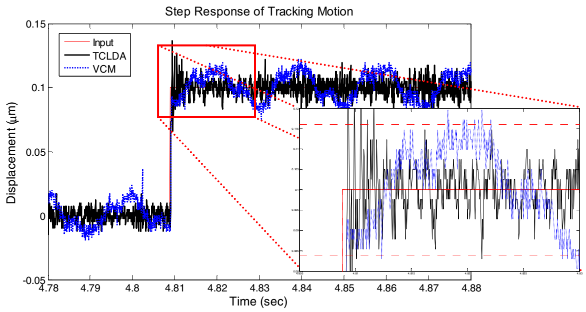


Fig. 11 Step response of 100 nm in the tracking motion

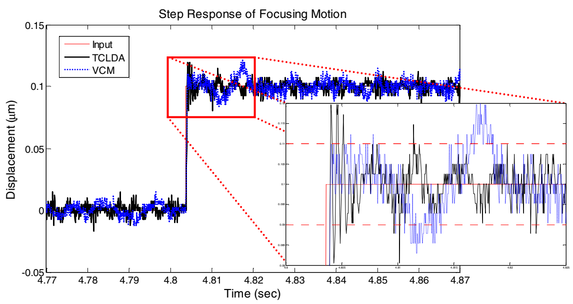


Fig. 12 Step response of 100 nm in the focusing motion

motions are shown in Fig. 13. It shows the track deviations for the TCLDA case are almost within the region of maximum allowable position error of ±16 nm, which is ±10% of pit width (0.16 μm) as the BD system uses the land and groove recording format. The largest position errors of the tracking and focusing motions for the VCM actuator are 32 nm and 21.6 nm, respectively. On the other hand, the TCLDA can achieve the tracking motion within 16 nm and the focusing motion within 10 nm.

IV. Conclusion

In this paper, a piezo-based optical pickup device with passive damping was proposed to enhance the capabilities of precision positioning and shock resistance in optical disk drives. It can be combined with a first stage large stroke actuator to form a novel dual-stage servo system for the next generation ODDs such as BD systems. The experimental results showed that there is a trade-off between the frequency bandwidth and the damping of the system, and then some parameters were studied. The cross effect between the tracking and focusing motions can be minimized with a good cymbal design. The closed-loop test showed that the configuration of the TCLDA case outperforms the current DVD VCM actuator in the tracking and focusing motions.

Acknowledgment

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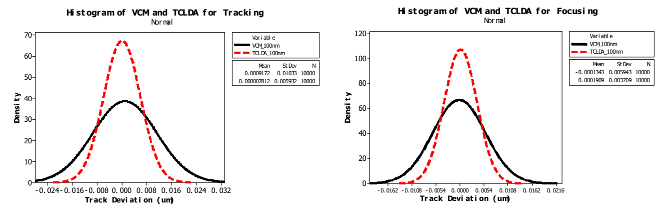

Fig. 13 Histogram (with fit) of the track deviations in the tracking and focusing motions

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