行政院國家科學委員會專題研究計畫　成果報告

微鏡面大轉動角度之電壓回授控制

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（一）中英文摘要

本研究計畫提議運用電壓迴授的方式，來對大型光學開關中的三維微鏡面體作大角度轉動控制，以擴大光訊號導引之範圍。計畫之背景源自於未來將建立以波長分工為基礎的全光學網路以提昇單一光纖傳輸之總頻寬，其中大型光學開關是所需最重要之元件之一，它負責將數千個輸入/輸出埠之任一波長訊號以微光學鏡面作直接反射導引，以取代傳統經由光-電-光轉換之傳輸模式，達到提昇傳輸頻寬、降低功率及成本的目的。

基於減少設計面積及操作耗能的考量，鏡面是以平行板式靜電力作驅動；經由電容式位置感測及迴授控制，我們可克服平行板電容驅動時存在的非線性與不穩定性，來達到所需的大角度轉動；來自於外界擾動所引起鏡面的角度變化將增加光訊號傳送時的耗損，迴授控制亦可進行干擾抑制以精準地控制角度。在控制系統的設計構想上，我們採用一個線性控制器和一個線性前置濾波器，其中控制器負責穩定平行板致動器之不穩定極點，增強系統穩定強韌性；前置濾波器則是置於迴路之前，負責角度追蹤的瞬態反應。我們原先計畫採用複晶矽製作微鏡面結構，而電路則置於另一 CMOS 晶片上；計畫進行中途我們決定將二者同時在單一 CMOS 晶片上結合，最主要在降低感測時的寄生電容，便於感測電路設計。

總體而言，本計畫旨在提出一個切實可行的控制方法解決平行板致動器之不穩定性限制，而大幅增加三維微鏡面體的轉動角度；這一點將攸關是否能大量增加鏡面數目至數千個而達到大型光學開關的系統需求。對於具有上千個微鏡面的大型光學開關而言，我們提出的線性控制電路在製作上可降低系統複雜度，因此有其必要性。在這篇結果報告中我們將呈現並討論目前之工作進度與成效。

In this project, we propose the use of voltage feedback to significantly increase the rotational angle of 3-D free-space micro-mirrors in order to facilitate the switching and routing actions of light in the large-scale optical switch. The project background originates from the development of the ultra-high bandwidth wavelength-division-multiplexing optical network in which the large 3-D optical switch is one of the most important components to handle the network traffic of thousands of input/output ports, allowing any input light signal to be routed to the desired output port. The traditional optical-electrical-optical transmission can thus be replaced to enhance transmission rate at reduced power and cost.

Designed micro-mirrors are driven by the parallel-plate electrostatic force based on the needs to decrease design area and consumed power. By use of the capacitive position detection and feedback control, the nonlinear and unstable characteristics resulting from the parallel-plate actuation can be resolved to achieve a large rotational angle that is beyond the pull-in limit. Also, output-disturbance rejection is simultaneously applied to suppress the externally-induced angular change, in order to reduce the insertion losses of light signals. The control system configuration requires the designs of two linear functional blocks, namely, a controller and a pre-filter. The

controller stabilizes the unstable pole within the loop, and enhances stability robustness. The pre-filter is placed in front of the loop to shape the input command and give the desired output transient response. Initially the polysilicon surface-micromachining process was selected for fabrication of the mirror, and the sensing and control circuits would be placed on a separate CMOS die; later we decided to integrate both of them together on a CMOS die, otherwise the large parasitic capacitance would cause significant signal attenuation and hamper the sensing circuit design.

To summarize, we propose a viable control methodology to resolve the electrostatic pull-in issue, and significantly increase the rotational angle of 3D micro-mirrors. With a large rotation, overall input/output ports of a large-scale optical switch can be increased to thousands to meet the system specifications. The relatively easy implementation of the proposed linear control circuits is necessary for reduction of system complexity, considering that a large-scale optical switch consists of thousands of controlled micro-mirrors. In this report, we will present and discuss the current status of the project.

（二）報告內容

（2.1）前言

One of the most critical components for realization of the all-optical network is the large-scale 3-D optical switches which direct the traffic of thousands of optical signals based on light reflection to the desired input/output ports. The key challenge for the desired application requires the realization of a 3-D optical micro-mirror that can achieve large rotation and accurate angular positioning while minimizing the system footprint and the signal attenuation as will. The research on 3-D optical switches has been actively pursued by many large optical-communication companies, for examples, Lucent, Nortel, etc. If successful, more data bandwidth can be provided with significantly reduced switching power that would not be possibly achieved by the conventional optical-electrical-optical (O-E-O) conversion.

（2.2）研究目的

Compared with other actuation mechanisms, driving the micromechanical mirrors by the parallel-plate electrostatic actuation is favorable due to its large energy density, immunity to temperature change, and the relative ease for implementation. However its maximum allowable displacement is known to be only one-third of the gap for open-loop operation, which also limits the rotation angle of torsional actuators.

The purpose of this project is aimed at using the closed-loop feedback control to extend the travel range of the micro-actuator beyond the limit. For proof of the concept, we plan to first experimentally demonstrate the success of closed-loop servo by using a simple one-axis mirror design. The experience can then be extended to more complicated mirror designs tailored for commercial applications.

（2.3）文獻探討

The literatures regarding the mirror design, sensing circuit, and feedback control of parallel-plate electrostatic actuator are listed below. The most valuable reference would be [8], which provides many insights regarding the control system design.

Micro-mirror design:

[1] A.P. Neukermans and T.G. Slater, "Micromachined torsional scanner," U.S. Patent 5 629 790, May 13, 1997.

[2] A.P. Neukermans, T.G. Slater, and P. Downing, "Micromachined members coupled for relative rotation by torsional bars," U.S. Patent 6 044 705, July 1997.

[3] V.A. Aksyuk and D.J. Bishop, "Self-assembling micro-mechanical device," U.S. Patent 5 994 159, Nov. 1999.

[4] V.A. Aksyuk, F. Pardo, C.A. Bolle, S.C. Arney, and D.J. Bishop, "Lucent Microstar micromirror array technology for large optical cross connects," *Proc. SPIE*, vol. 4178, pp. 320-324, 2000.

[5] A. Gasparyan, V.A. Aksyuk, P.A. Busch, and S.C. Arney, "Mechanical reliability of surface-micromachined self-assembling two axis MEMS tilting mirrors," *Proc. SPIE*, vol. 4180, pp. 86-90, 2000.

CMOS sensing circuit:

[6] P. R. Gray and R. G. Meyer, Analysis and Design of Analog Integrated Circuits, John Wiley & Sons, Inc., 3rd ed., 1993.

Position servo of parallel-plate micro-actuators:

[7] R. Nadal-Guardia, A. Dehe, R. Aigner, and L.M. Castaner, "Current drive method to extend the range of travel of electrostatic microactuators beyond the voltage pull-in point," *J. of Microelectromechanical Systems*, vol. 11, no. 3, pp. 255-263, June, 2002.

[8] M. S.-C. Lu and G. Fedder,"Control of a parallel-plate microactuator beyond the pull-in limit," in *Technical Digest Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, USA, pp. 255-258, June, 2002.

（2.4）研究方法

The goal of this project is to design and implement the micro feedback control system for servoing an electrostatic parallel-plate actuator beyond the pull-in limit of one-third of the gap, since the increase of controlled light-beam angles is greatly desirable for large-scale 3-D optical switches. The controlled plant is the electrostatic micro-mirror whose rotational angle is detected by a capacitive sensor, and the sensed signal is subsequently processed by a controller that drives the mirror. The greatest challenge for the controller design would be the stabilization of non-linear and unstable plant beyond the pull-in limit.

The main tasks of the project would be divided into the followings:

(1). Design, fabrication, and testing of the micro-mirrors. The desired switching speed is around a few *ms*, which results in the mechanical design with a natural frequency in the kHz range. For electrostatic actuation, the maximum applied voltage of the mirror is set less than 10 volts such that it can be produced by high-voltage CMOS transistors. There are two processes considered for fabrication: one is the conventional three-layer polysilicon surface-micromachining process using SiO_2 as the sacrificial material, and the other is based on CMOS-MEMS micromachining which can use the existing metallization and dielectric layers as the structural layers, and use aluminum as the sacrificial layer for structural release. The CMOS-MEMS approach has the advantage of monolithically integrating the micromechanical structures with all the necessary sensing and control circuits. For demonstration of a large rotational angle, we focus on the 1-D mirror design that has a light-reflecting plate on the top with two connected torsional bars (springs), and sensing and actuation electrodes at the bottom.

(2). Design, fabrication, and testing of the capacitive position sensor. The mirror angle is detected by a single-ended sensing scheme through modulation, amplification, and demodulation. The input capacitance of the pre-amplifier, which forms a capacitive bridge with the sensing capacitance, has to be minimized to enhance the capacitive sensitivity. One of the appropriate pre-amplifier topologies that can provide a small input capacitance, and at the same time, an accurate gain, is the differential input stage using the diode-connected CMOS transistors. By analysis its gain depends only on the ratios of the transistor dimensions. The accurate gain is desirable for reducing the plant uncertainties among the controlled micro-mirror array, thereby minimizing the fixed controller bandwidth. The selected modulation frequency (namely, the pre-amp bandwidth) should be high (~ 5 MHz) to allow a better high-pass filtering of the feedthrough due to the base-band actuation signal. The demodulator design can be a balanced analog multiplier (e.g., the Gilbert cell) that also minimizes the feedthrough, which eventually appears at the sensor output as a false sensed signal.

(3). Design and testing of the controller. The electrostatic micro-mirror can be described using the simple second-order mass-damper-spring model driven by the parallel-plate electrostatic force. Given the non-linear and unstable characteristics of the plant, the design of the controller is based on stabilization of the linearized plants along the motion trajectory, and the use of disturbance rejection to suppress the effects of the differences between the real and a family of linearized plants. A pre-filter is added in front of the feedback loop for shaping the input command to get the desired transient response. The non-linear squeeze-film damping coefficient in the plant model is a function of gap between the plate and electrodes. The coefficients can be obtained by a series of Spectre simulations using parameterized damping models written by the Verilog-A language.

（2.5）結果與討論

Currently we are behind the proposed schedule for demonstration of the closed-loop servo of the micro-mirror. The research is still in progress for characterization and testing of the mirror and the capacitive sensor, and requires about two more months for completion. We herein present the results from the past 12 months regarding the micro-mirror, the capacitive sensor, and the controller design.

(1). Polysilicon micro-mirrors

The fabricated polysilicon surface-micromachined micro-mirror with a resonant frequency of 1 kHz and a driving voltage less than 10 V is shown in Figure 1. This simple design has a large, underlying actuation electrode on one side, and a large sensing electrode on the other side to maximize the respective capacitive transduction. The holes on the plate help the release of the structure. We are still tuning the recipe for better release of the structure before the static and dynamic responses of the mirror can be measured by the WYKO optical profiler and the Laser Doppler instrument, respectively. However, integration of the mirror with the sensing and control circuits would be difficult due to the large parasitic capacitance seen at the sensing node, which is about two orders of magnitude larger than the sensing capacitance, and would result in a significant signal attenuation. We thereby would shift more of our research efforts to the integrated CMOS-MEMS micro-mirror.

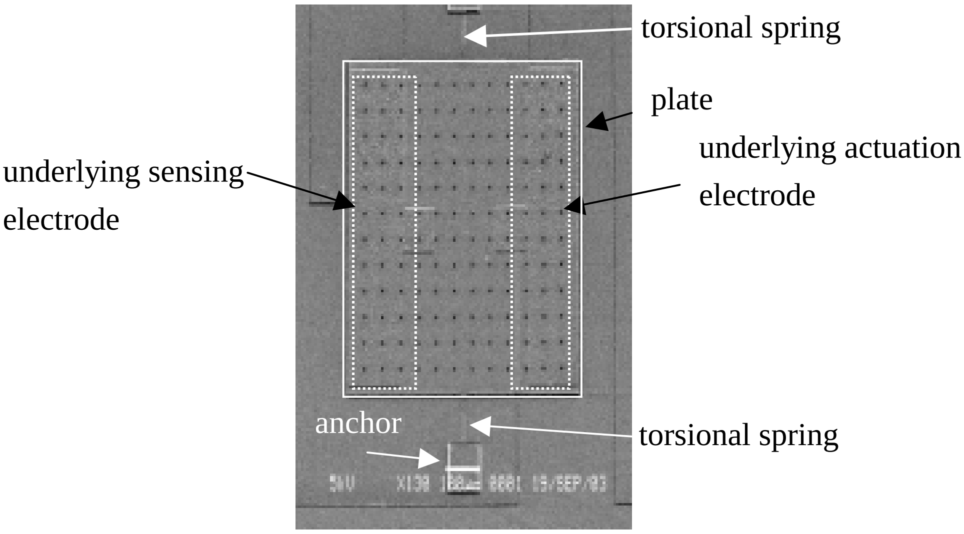

Figure 1: SEM illustrating the top view of the fabricated polysilicon micro-mirror.

(2). Integrated CMOS-MEMS micro-mirror

We used the TSMC 0.25 μm 1P(Polysilicon)5M(Metal) CMOS process for fabrication of the micro-mirrors, and the dies (CIC M25-92D) were received on October 9, 2003. The scheduled tasks before the final closed-loop control demonstration include: (1). pre-amp test, (2). release of the CMOS-MEMS micro-mirrors, (3). static test of the micro-mirrors (θ vs. applied voltage), and (4). measurement of frequency responses of the micro-mirrors.

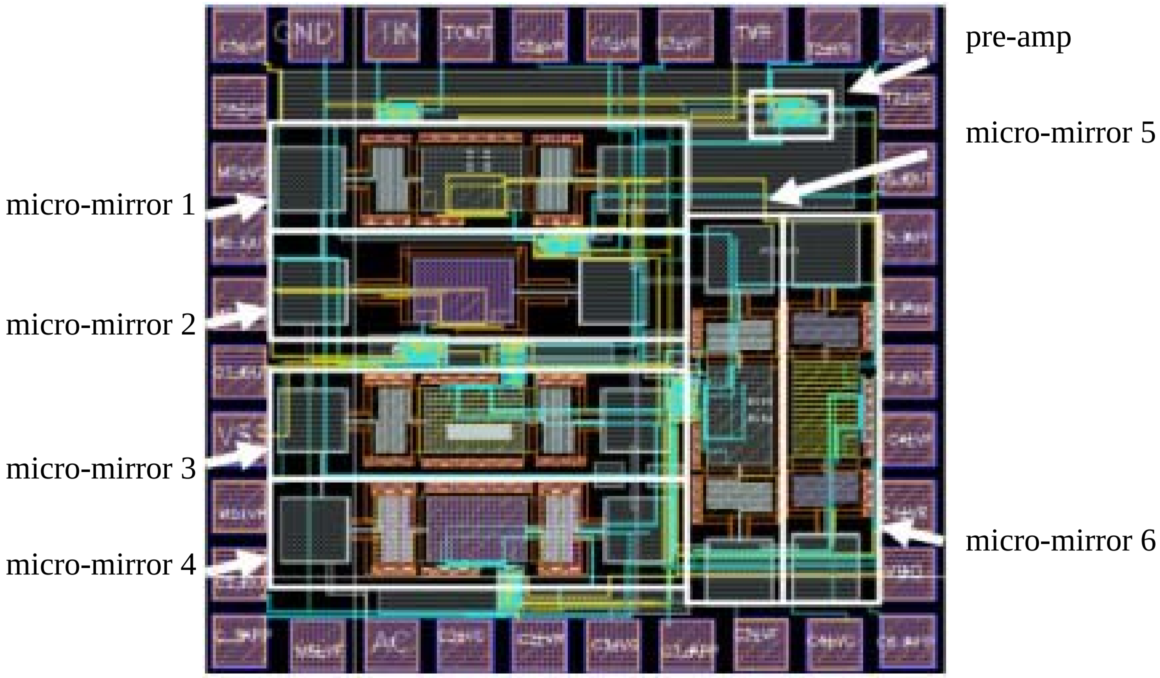

Figure 2: CMOS layout showing six integrated mirror designs, and one test pre-amp.

A total of six mirror designs were placed on the die, with the gap spacing from 0.57 to 3.71 μm to achieve maximal rotation from 1° to 5°, respectively, for less than 10 volts. Figure 2 is the complete layout, and Figure 3 is one of the mechanical designs simulated by the finite-element analysis (ω_n = 8 kHz). Meandering springs, instead of straight beams, were used as plate suspensions in order to avoid structural buckling. This mirror used metal-5 and the oxide layer (between metal-4 and metal 5) to create a 2-μm thick top plate, and the gap underneath was created by the metal2-to-metal4 thickness that would be sacrificially etched. The expected rotational angle is 4.3° for the design. Metal-1 was used as the bottom electrodes for actuation and sensing.

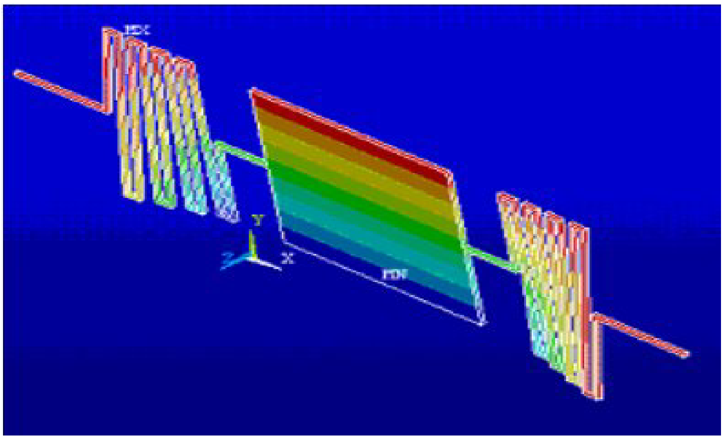

Figure 3: Finite-element analysis of CMOS-MEMS micro-mirror.

The CMOS capacitive sensing pre-amp consists of two cascaded differential-gain stages followed by the common-drain output stage. Each gain stage used the diode-connected NMOS transistors, instead of PMOS, as the load to provide a proper amplification (2 to 3) without nonlinear distortion. For an output capacitance around 20 pF (currently the mixer is implemented off-chip), the total pre-amp gain is around 6 (±2%) up to 1 MHz, and the -3dB frequency is around 8 MHz, as shown in Figure 4.

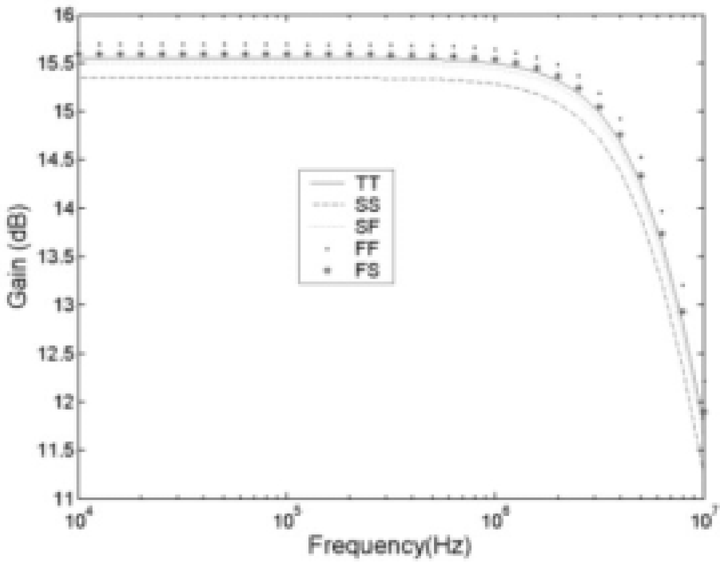

Figure 4: Corner analysis of the pre-amplifier magnitude response illustrating the possible gain variations.

The equivalent input-referred angle noise of the capacitive sensor is determined by the circuit Johnson noise and the thermomechanical Brownian noise. With an estimated pre-amp input capacitance of 70 fF, a capacitive sensitivity of 16 mV/μm (@gap = 3.7 μm), and a quality factor Q = 1, the calculated noises are 3.2×10^{-13} m/√Hz (or 6.4×10^{-9} rad/√Hz) and 3.5×10^{-13} m/√Hz (or 7×10^{-9} rad/√Hz), respectively. The total noise is about 6.7×10^{-13} m/√Hz (or 1.34×10^{-8} rad/√Hz). At 1 kHz servo bandwidth, the estimated minimum detectable signal is 4.2×10^{-7} radian (2.4×10^{-5}°).

(3). Controller design

The electrostatic micro-mirror can be described using the 2nd-order model. Currently the Verilog-A squeeze-film damping model is employed in the Spectre simulation to obtain the damping coefficients at various rotational angles. Then the coefficients will be inserted into a Matlab script to obtain a proportional-gain controller that has maximized phase margins at various rotational angles. The controller does not include an integrator, since the 90-degree phase lag would reduce the phase margin tremendously.

（三）參考文獻

More technical contents can be found in:

陳永霖, Servo Control of Micro-mirrors for Optical Communication, Master Thesis, Institute of Electronics Engineering, National Tsing Hua University, May, 2004.

（四）計畫成果自評

The current results can be evaluated using the following criterion:

(1). Contents

Originally we proposed the polysilicon surface-micromachining process as the fabrication platform; however, due to the small sensing capacitances in our design, the capacitive sensing circuit would be difficult to be realized off-chip. We then shifted our efforts to the integrated CMOS-MEMS micro-mirror in order to perform on-chip sensing. The dies were received around the report due date because of the late submission. The open-loop testing of the respective mechanical and electrical components would start in the mid-October, followed by the final servo test expected in the late December.

The micro-mirror design was not ideal in the sense for future commercialization; one reason was due to our preset goal to use a simpler design to demonstrate the closed-loop servo, and the other was constrained by inability of the CMOS-MEMS process to fabricate a 3-D large-rotation mirror. We are aware that there is on-going research effort (Department of Power Mechanical Engineering, National Tsing Hua University) devoted on 3-D mirror design and fabrication. The collaboration can be expected in the future.

(2). Publication

Accurate and large angular control of electrostatic micro-mirrors is critical for realization of 3-D optical switches. Until now very few discussions can be found in literatures. The bottleneck lies in the ability to integrate the sensing circuit, and to implement a robust control system as well. We believe that this research work would be of great interest to both the MEMS and optical communications communities, and the results, if successful, can definitely be published in the related journals.

可供推廣之研發成果資料表

☐ 可申請專利　　× 可技術移轉　　　　　　　　　　　　日期：92 年 10 月 13 日

國科會補助計畫	計畫名稱：微鏡面大轉動角度之電壓迴授控制 計畫主持人：盧向成 計畫編號：NSC 91－2218－E－007－044－ 學門領域：自動化
技術/創作名稱	非線性非穩定性平行板靜電致動器之伺服控制
發明人/創作人	盧向成
技術說明	中文：平行板靜電致動器本身為非線性，同時在其位移超越三分之一原始間距時將出現不穩定極點。為保證系統在此工作區域的穩定性，控制器設計採用線性化、以及消除被控體不確定性之技巧，克服其非線性特性及不穩定極點；除此之外，在閉迴路之前的前置濾波器負責調整輸入命令以得到所想的瞬態輸出反應。
	英文：The parallel-plate electrostatic micro-actuator is intrinsically nonlinear, and is unstable beyond one-third of the initial separation. To guarantee system stability in this range, the controller design uses the linearization technique, along with sensitivity reduction, to overcome the nonlinearity and the unstable pole of the plant. In addition, the pre-filter placed in front of the feedback loop shapes the input command to get the desired transient response.
可利用之產業 及 可開發之產品	Optical communication (3-D optical switch), Data storage (read/write head micro-actuator), Force-balanced inertia sensor

技術特點	(1).Use a two-degree-of-freedom control system configuration to successfully servo an unstable nonlinear plant. (2). The implementation requires only linear circuits.
推廣及運用的價值	Very useful for situations where the plants are nonlinear and unstable, and the controllers need to be implemented by analog circuits for minimal complexity.

※ 1.每項研發成果請填寫一式二份，一份隨成果報告送繳本會，一份送貴單位研發成果推廣單位（如技術移轉中心）