A High Resolution Actuator Design For Laser Beam Steering Applications

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ABSTRACT

An actuator design for beam steering micromirrors is reported. Coarse positioning is achieved with a 4-bit mechanical digital to analog converter [1]. The exact position is sensed by a set of lateral comb fingers and controlled through the leastsignificant bit of the DAC, which is embedded in a feedback loop. The actuator is designed for bilateral actuation of +/- 3μ m with a resolution of 6nm providing a maximum force of 1mN. The voltage of operation is 30V. A single-mask SOI process with minimum feature size of 2μ m is used.

I.INTRODUCTION

Micromirrors used for precision beam steering place specific force, displacement and resolution requirements on the actuators. A large force over a long displacement must be supplied for providing large angles of rotation. A single actuator working under those conditions would require an inconveniently high driving voltage. As an alternative several actuators operating on a system of levers can be used to obtain quantized displacements. Lower operation voltages are achieved through force multiplication. Such a system, called a mechanical digital-to-analog converter (DAC), has been reported in [1], [2] and [3]. Limitations due to various sources such as spring non-linearity, beam bending and processing tolerances restrict the accuracy to several hundred nanometers. In this work a feedback loop around the LSB of the MEMDAC is designed for canceling displacement errors. An overall block diagram is given in Fig.1. This approach uses the DAC actuators A_1 to A_3 for rough quantization of the displacement and the analog feedback loop for precise adjustment around each digital level. The force generated by the comb drive of the LSB (actuator A_{a}) is amplified by the mechanical structure of the DAC, resulting in low operation voltage for the analog part. For this particular application, a maximum force of 1mN and a bidirectional motion of +/- 3µm are required. Steering accuracy of 1mrad sets a 6 nm resolution goal for the actuation.



Fig.1 Overall block diagram of the system

II. MECHANICAL DESIGN

DAC Design

A lever driven from either end can be used as a mechanical summing node. A previous design [1] uses cascaded lever arms for building a mechanical DAC whose operation is similar to an electrical R-2R digital-to-analog converter. As shown in Fig.2, the output displacement is equal to the average of the two displacements. Since the lever arm is a passive device, the forces must be amplified by two according to the principle of energy conservation. Consequently, in a network of lever arms, the force and displacement created at the output by the Nth bit are:

$$F_{OUT(N)} = 2^{N} F_{(N)}$$
 $\Delta X_{OUT(N)} = \frac{\Delta X_{IN(N)}}{2^{N}}$

As described in [2], lever networks may have substantial nonlinearity and gain errors. One of the major contributors to the position error is the mismatch of gap spacing. The required accuracy of 6nm cannot be achieved through precise gap stop positioning due to general processing limitations. Another main error source is the finite stiffness of the coupling beams, the levers and the actuators. When one end of the lever is actuated, the lever pivots around the other end and applies



Fig.2 DAC lever arm

moment to the beams. Assuming small angular displacements, the amount of rotation is $\Delta x_{IN}/L$. As the tips of the beams bend more, they become more compliant in the direction in which they provide coupling. Increasing the lever arm length was shown to decrease the conversion error until the lever arm itself starts bending [2]. Due to thicker device layers in the SOI process, longer lever arms can be used without significant bending. In the current design a displacement of 3 μ m at the tip of a 1000 μ m lever results in a 3 mrad (~0.172 deg) rotation.

Support beams suspend the levers at the end which is coupled to the next stage. A 2 μ m x 400 μ m beam bends less than 1 nm under the gravitational force acting on the lever. Longer support beams are preferred for reducing the loading on latter stages. The ends of the coupling beams are thinned to allow the levers to pivot when the actuator is activated.

Actuator Design

The first three bits are digitally activated - they are either at $+3 \mu m$ or $-3 \mu m$ positions. A parallel plate gap-closing actuator is suitable for these stages. The final position of the rotor is determined by gap stops preventing the plates which are at different potentials from touching each other. Cascaded levers allow the higher force density of parallel plate actuators to be utilized without implementing a complicated electronic controller for stabilization beyond pull-in. However, as mentioned above, gap stops cannot be located with the desired accuracy. In other words, improving the mechanical design of the lever system is not sufficient for achieving the pointing accuracy of the mirror. In order to solve this problem, an

analog actuator is employed for controlling the fine positioning. Since the analog actuation is in the LSB, the actuator must provide a displacement of +/- $2^N * \Delta x_{error}$ in addition to the +/- 3 µm.

Shuttles carrying the fingers of the gap closing actuators are supported by beams spanned parallel to the nominal lever orientation. This prevents the shuttle from rotating at the same angle as the lever. Even a small rotation of 3 mrad would bring the tips of the actuator fingers $3mrad*L_{finger}$ closer to the stator fingers. For a 100 μ m finger this corresponds to 0.3 μ m (30 % of the final gap), which may cause pull-in instability. FEM simulation in ANSYS 5.7 was used to verify this approach.

The MSB lever experiences the largest structural deflection, since it is directly subjected to the mirror loading and the largest actuation force. Bending of the lever and the beams makes the output displacement smaller than the ideal case shown in Fig. 2. The worst case for the MSB lever occurs when both ends are actuated in the same direction. The torque arm connecting the mirror to the actuator bends the center of the lever in a direction opposite to the motion at the ends. The lever width can be increased for increasing the lever stiffness in the direction of bending. FEM simulations were used to investigate the worst case (3 μ m displacement at the ends) for a 1000 μ m lever for different widths. The results are given in the table below.

 Table 1. Output errors for different widths

Width	50µm	100µm	150µm
Output	111 nm	15 nm	7nm
Error			



Fig. 3 ANSYS simulation of MSB



Fig. 4 Feedback control loop of the LSB

Bigger output errors require a larger range of motion for the analog stage. The number of fingers must be increased in order to drive the additional load resulting from the larger motion. On the other hand, increasing the width of the lever beyond 100 μ m has a minor effect on the error performance. FEM simulation results given in Fig.3 show a worst case error from the MSB stage lever (100 μ m X 1000 μ m) of ~ 15 nm. Since the forces decrease towards the LSB, the errors created in the later stages are considerably smaller than 15 nm. The analog bit of the actuator was designed to be able to correct an error of 300 nm, considereing gap stop variations and other mismatches.

Linear voltage-to-position actuation can be achieved by using a differential comb drive structure in the LSB stage. This requires biasing all moving structures at either +15 V or -15 V. A high frequency square wave drives the differential sense capacitors for position readout as described later. Bi-directional actuation requires allocating two stator fingers for each rotor finger. However, the absence of a metal layer providing the necessary electrical connections makes this design impossible to implement in the available process. An additional actuator with the positions of rotor and stator fingers swapped was used for actuation in the opposite direction. The island of silicon holding the stator fingers of the actuator must be electrically isolated from the rest of the substrate. Using a separate bonding pad for each actuator can provide the required isolation.

IV. SYSTEM DESIGN

Precise positioning is achieved through embedding the mechanical structure into an analog control loop. A block diagram of the loop is given in Fig.4. The displacement of the actuator is sensed as capacitance change on the sense comb fingers. A capacitance to voltage converter provides voltage proportional to displacement. A conceptual schematic diagram of the C/V converter is given in Fig.5. High frequency square wave is applied to the structure modulating the signal at the output of the C/V converter. Direct demodulation of the signal at this point has the disadvantage of translating any offset and low-frequency noise generated by the C/V converter to high frequencies. In an open-loop system those high-frequency components can be easily filtered. Low-pass filtering inside a feedback system however is limited by stability constraints. As a result substantial high-frequency components are present in the signal after demodulation and the subsequent amplifiers are easily overloaded. A correlated double sampling scheme overcomes those disadvantages by introducing different transfer functions for the signals generated before and after the modulation. The two sample-andhold blocks in Fig.4 are clocked on opposite edges



Fig.5 C/V converter

of the demodulating signal and their outputs are subtracted. This operation demodulates all modulated signals while the signals generated after the modulation point are differentiated. As a result offset and low-frequency noise are cancelled. Amplifier thermal noise above the Niquist frequency of the sample-and-hold is aliased by the sampling operation. The effect of this noise on the noise floor however is less significant than the effect of flicker noise in the band of interest.

Since the mechanical element has a second-order transfer function with a pair of complex poles a compensator providing phase lead is added for



Fig. 6 Loop-gain frequency response

stability. An error amplifier realizes proportional control. The input to the system is generated by an electrical DAC whose three most significant bits are also applied to the mechanical DAC. The error amplifier drives the mechanical structure through the feedback combs connected to the LSB of the mechanical DAC.

The frequency response of the feedback loop is given in Fig.6. The loop is designed for a loop-gain of 39dB and a phase margin of 60deg. Settling time of 150nsec with a step input is obtained.

V. CONCLUSION

An actuator for beam-steering micromirrors was designed in a $2\mu m$ SOI process. The system is required to provide a displacement of +/- $3\mu m$ with a resolution of 6nm and a maximum force of 1mN. Input signals at frequencies up to 3kHz should be processed. ANSYS and MATLAB simulations indicate the feasibility of this design. The layout of the actuator is given below.

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