RUGGED BOARD-TO-BOARD OPTICAL INTERCONNECT WITH CLOSED-LOOP MICROLENS SCANNER

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ABSTRACT

This paper discusses a free-space optical interconnect system capable of dynamic closed-loop optical alignment using a microlens scanner and a proportional integral and derivative (PID) controller. Electrostatic microlens scanners based on combdrive actuators are designed, fabricated, and characterized with vertical cavity surface emitting lasers (VCSELs) for adaptive optical beam tracking in the midst of mechanical vibration noises. We demonstrate optical beam positioning noise reduction of approximately 20 dB with a 400 Hz bandwidth in the presence of up to a 3g ($g = 9.8m/s^2$) vibration.

INTRODUCTION

Optical interconnect technologies can significantly increase the chip-to-chip and board-to-board communication bandwidth, relieving the bottleneck of traditional backplane-based computer systems [1]. Especially, free-space optical interconnects using arrays of VCSELs and photo-receivers allow for cheaper, lower power, higher bandwidth, and more compact alternatives to traditional copper-based interconnects [1-4]. However, alignment between the optical source and detector is critical for optical interconnect applications, and mechanical noises due to vibration and temperature variation inside the computer systems have prevented the wide deployment of such technology.

We present an adaptive free-space optical interconnect using electrostatic microelectromechanical systems (MEMS) lens scanners with closed-loop control to circumvent such difficulties. Although various strategies to adaptively compensate for the misalignment using MEMS devices [3, 4] with feed-forward [5] and feedback control [6] have been attempted, a vibration-resistant free-space optical interconnect system with an intensity-modulated optical beam has never been fully demonstrated. Figure 1 shows the schematic view of our device correcting a misalignment Δx by steering the optical beam across the board-to-board gap.

Figure 1: Schematic diagram of MEMS based free-space board-to-board optical interconnect. Although the optical transmitter and receiver are laterally misaligned by Δx , the MEMS microlens scanner steers the optical beam to the correct position.

DEVICE DESIGN AND FABRICATION

The light source (VCSEL) is located near the back focal plane of the polymer microlens (focal length: f), and the beam deflection angle due to the MEMS lens scanner is approximately given by $(\theta_x, \theta_y) = (d_x/f, d_y/f)$, when the microlens lateral displacement on the X and Y direction are d_x and d_y , respectively ($f \gg d_x, d_y$) [3, 7]. For example, to compensate for the misalignment of Δx at the board-to-board spacing of d , as schematically depicted in Fig. 1, the microlens should be laterally translated by $\Delta x f/d$ toward the photodetector (PD). Design parameters for the microlens size, displacement requirement, and footprint are summarized in Table 1.

Table 1: Design parameters for MEMS lens scanner devices.

Parameter	Value
Board-to-board spacing, d	2 cm
Maximum misalignment, Δx_{max}	500 μm (one direction)
Mechanical noise bandwidth	400 Hz
Microlens scanner footprint	1.8 mm $\times$ 1.8 mm
Microlens diameter	300 μm
Combdrive gap width	3 μm
Combdrive finger length	40 μm

To compensate for the misalignment in both X and Y direction, the MEMS lens scanner should be able to steer the optical beam in two orthogonal directions. We use electrostatic combdrive actuators to laterally scan the lens [4, 7, 8], and the four operating modes (left, right, up, and down) are schematically described in Fig. 2. For this paper, however, only one-dimensional actuation (right direction in X -axis with outer combdrives as shown in Fig. 2a) is used to demonstrate vibration-resistant optical interconnect.

Figure 2: Scanning modes of operation for two orthogonal axes. Electrical isolation trenches are indicated by red lines.

Figure 3: Fabrication process flow of two-dimensional MEMS lens scanner. (a) DRIE front side isolation trenches on 20 μm device layer. (b) Deposit and pattern low-stress nitride and polysilicon for electrical isolation. (c) DRIE for MEMS structures, such as combdrives and springs. (d) DRIE backside through-wafer etching on 500 μm -thick silicon substrate. (e) HF vapor for release etch on 1 μm -thick buried oxide layer. (f) Directly apply ultraviolet-curable polymer on the lens frame, and cure for 5 minutes.

Figure 4: Scanning electron micrograph (SEM) and microscope images of the fabricated MEMS devices. (a) SEM of the entire device after front side etching (Fig. 3c). (b) Zoom in on comb structures and lens frame. The outer diameter of the lens frame is 300 μm . (c) An optical microscope image of complete MEMS structure with polymer microlens. (The electrical isolation steps (Fig. 3a and 3b) are skipped.)

Our MEMS lens scanner is fabricated by bulk-micromachining of 6-inch silicon-on-insulator (SOI) wafer with a 20 μm device layer. The details of our process flow and the pictures of the fabricated devices are shown in Fig. 3 and 4, respectively. A deep reactive ion etching (DRIE) process is used to define front and backside features with high aspect ratios. A backside through-wafer etch (Fig. 3d) was performed for two reasons, to create an optical path for the laser output and to eliminate undesired out-of-plane electrostatic actuation.

An ultraviolet-curable polymer lens, with a refractive index of 1.55, was used to collimate and deflect the optical beam from a directly-modulated VCSEL with the center wavelength of $\lambda=850$ nm (Fig. 3f and 4c) [4, 8]. Assuming the beam profile evolution according to Gaussian beam theory, the beam diameter at the scanning lens is approximately given by $2\sqrt{d\lambda/\pi}$, if the board-to-board spacing, d , is twice the Rayleigh length of the collimated beam. The clear aperture size of the steering lens is designed to be larger than the optical beam diameter to reduce any clipping loss.

For two-dimensional actuation of the polymer lens, low stress nitride and polysilicon can be used to create plugs to electrically isolate yet mechanically couple segments of the device (Fig. 2, 3a, and 3b). The electrical isolation plug locations are indicated by short red lines in Fig. 2. Because of these electrical isolation trenches, only one device layer is required for two-dimensional lateral motion. Previous works using electrostatic actuators, such as [7], use two device layers for mechanical/electrical isolation.

EXPERIMENTS AND RESULTS

We first measure the static and dynamic characteristics of the MEMS lens scanner device. Figure 5a shows the quadratic relationship between the laser beam deflection angle (θ_x) and the input voltage (V_x). The focal length of the lens is estimated to be $f \sim 1.3$ mm, and the optical beam position (d_x) is measured by the PSD as shown in Fig. 6 ($\theta_x = d_x/f$). The lateral microlens displacement is very small compared to the microlens diameter of

Figure 5: Static and dynamic characteristics of the MEMS lens scanner for its X-axis motion (Fig. 2a). (a) Measured and fitted optical beam deflection angle (θ_x) as a function of input voltage (V_x). (b) Measured and fitted transfer functions when the input bias voltage is 22V. The output signal amplitude is normalized to the DC level.

300 μm ($d_X < 10 \mu\text{m}$ at $V_X = 25 \text{ V}$), and, therefore, the steering angle dependant clipping loss is negligible. The maximum input voltage before the combdrive pull in effect is observed is approximately 47 V, which corresponds to a single sided maximum beam deflection of about 1° . The lens focal length is currently not optimized for the board-to-board spacing of 2 cm as described in Table 1, but adjusted for the distance between the transmitter and receiver in our system-level experimental setup shown in Fig. 6 (~130 mm).

The transfer function of the device at the input bias voltage of 22 V is shown in Fig. 5b, which indicates that the resonant frequency of the lowest mode (translational motion along the X-axis) is around 640 Hz. To obtain transfer function measurements, the small signal amplitude is kept small ($\sim 1 \text{ V}$) to prevent nonlinear effects. Under this regime, the MEMS scanner can be modeled as an underdamped second-order linear system with the natural frequency of f_0 . Under this model, the fitted transfer function of the MEMS structure in Fig. 5b is given by $F(s) = \omega_0^2 / (s^2 + 2\zeta\omega_0 s + \omega_0^2)$ where the angular natural frequency and the damping ratio are $\omega_0 = 2\pi f_0 = 2\pi \times 644.5 \text{ Hz}$ and $\zeta = 0.0234$, respectively. Our computer simulations based on finite element methods confirm our measurements, and the estimated resonant frequencies of the two lowest order modes along the X and Y direction are 0.64 and 1.6 kHz, respectively, when the polymer lens mass is taken into consideration. According to the simulation results, the resonant frequencies for other higher order modes are much greater than our target mechanical bandwidth of 400 Hz as well as the resonant frequencies for the two lowest order modes. For example, the third mode is the in-plane torsional motion, and its eigen frequency is 2.6 kHz.

As described in Fig. 1 and 6, our system-level experimental setup is designed to simulate one-dimensional mechanical vibration between two computer boards and to use the MEMS lens scanner to eliminate the mechanical noise of free-space optical interconnect. Instead of vibrating the whole transmitter or receiver, we used a 45° turning mirror and a voice coil shaker to introduce time-varying translational offset $\Delta x(t)$ to the optical beam position on the PSD and a high-speed photodetector. The VCSEL with the center wavelength of $\lambda = 850 \text{ nm}$ is directly modulated at 100 Mbits/s with $2^{23}-1$ pseudo random bit sequence using a pulse pattern generator, and the MEMS lens scanner collimates and steers the optical beam toward the PD in the receiver side. The data rate of the optical communication system is currently limited by the bandwidth of the PD and VCSEL modulation, which can be significantly improved. The bandwidth of the PSD is approximately 10 kHz, and, therefore, its output signal is almost insensitive to the high-speed intensity

modulation, and proportional to the optical beam position.

A data acquisition system obtains the optical beam position information by sampling the PSD signals at a rate of 20 kHz, and a software-based real-time PID controller calculates and generates the closed-loop feedback voltage signal to the MEMS lens scanner within a $50 \mu\text{s}$ period. The PID controller has a transfer function of $H(s) = sK_D + K_P + s^{-1}K_I$, and, therefore, the cascaded transfer function of the MEMS device and the PID controller becomes

Figure 6: Schematic diagram of our experiment setup.

BS: Beam splitter. PPG: Pulse pattern generator at 100 Mbits/s. PD: high-speed photodetector with 100 MHz 3-dB bandwidth.

Figure 7: Simulated response curves of the PID ($H(s)$) controller and MEMS device ($F(s)$). (a) The magnitude of the transfer function shows the tuned PID controller zero cancels out the resonant frequency of the MEMS device. (b) The phase plot of the PID and MEMS transfer function.

Figure 8: Measured eye diagrams (upper row) and optical beam positions (lower row) in the four different operating regimes. The optical beam position signals are measured when the VCSEL is not modulated. When the shaker is turned on and the feedback control mechanism is not used, the signal quality is severely degraded and the eye is almost closed as shown in Fig. 8c. However, the active optical tracking, with the MEMS lens scanner, can compensate for the mechanical vibration, and restores signal quality as shown in Fig. 8d.

$F(s)H(s)$. By tuning the coefficients K_D , K_P , and K_I , we are able to change the zeros of the PID controller in the numerator, and compensate for the underdamped response of the MEMS lens scanner [9]. In our experiment, the PID zero effectively cancels out the MEMS pole at 644 Hz as shown in Fig. 7. The coefficients used are $K_P = 2.58 \times 10^{-3}$, $K_I = 871$, and $K_D = 4.84 \times 10^{-5}$, which are sensitive to VCSEL position, ambient light, and sampling frequency. Our device is demonstrated under room temperature with ambient room light fully exposing the system.

The eye diagrams and beam position signals in Fig. 8 demonstrate the improved optical communication link with the closed-loop feedback microlens scanner. With Gaussian white noise vibration with a standard deviation of $190.3 \mu\text{m}$, the eye diagram is severely degraded as shown in Fig. 8c. However, when the feedback controller is turned on, the standard deviation of the noise attenuates by a factor of over 20, which results in an even cleaner signal than the static case in Fig. 8a.

Figure 9: (a) Power spectral density of beam positioning noise when the closed-loop feedback controller is turned on and off. (b) Noise attenuation factor obtained by dividing the signal without feedback over with feedback. Noise attenuation cutoff near 400 Hz is due to the mechanical vibration bandwidth of the voice coil shaker itself.

Finally, Fig. 9 shows that the demonstrated system is capable of a noise attenuation factor of about 100 with a bandwidth of 400 Hz. We measured the optical beam position as a function of time using the PSD while the driving signal to the voice coil shaker is white Gaussian. By taking the Fourier transform of the measured PSD output, we can estimate the power spectral density of the beam positioning noise. The cutoff frequency of the noise power spectral density at ~ 400 Hz when the feedback control is off is due to the maximum driving frequency of the mechanical shaker. Because of force constraints, the shaker cannot be driven much faster than the cutoff frequency, and this fact limits our ability to measure the noise power spectral density beyond the cutoff frequency. The voice coil shaker also has several resonant modes at low frequencies (<100

Hz), which distorts the power spectral density curve. By comparing the noise power spectral density curves before and after the feedback controller is turned on, we can conclude that the MEMS lens scanner can suppress the beam positioning error significantly at least up to 400 Hz.

CONCLUSION

We successfully demonstrate a one-dimensional robust optical interconnect with a closed-loop microlens scanner capable of correcting mechanical misalignment up to 100 times with a bandwidth of 400 Hz. We present eye diagrams to show the dramatic improvement of the free-space optical link quality in the midst of vibration noise with and without the feedback control activated. The MEMS scanner was designed, fabricated, and characterized with an intensity-modulated VCSEL, and has a maximum beam deflection of $\sim 1^\circ$ with a resonant frequency of 644 Hz in the X direction. A PID controller was tuned to provide a stable feedback control for reliable optical beam tracking. Aside from optical interconnects, these types of devices can be applied to an array of optical systems, such as digital imaging, photo-lithography, and optical monitoring/tracking, that require fine position control and real-time adaptability. We believe our device can provide a compact, low cost, and low power solution to adaptive optical steering systems.

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