Two-Axis MEMS Lens Alignment System for Free-Space Optical Interconnect

Brian E. Yoxall, Member, IEEE, Robert Walmsley, Huei-Pei Kuo, Shih-Yuan Wang, Fellow, IEEE, Mike Tan, and David A. Horsley, Member, IEEE

Abstract—We present a two-axis microelectromechanical systems (MEMS) lens aligner with a 260 \( \mu \text{m} \times 220 \mu \text{m} \) translation range that positions a 6.35 mm lens with focal length \( f = 12.1 \text{ mm} \) for alignment compensation of free-space optical interconnects (FSOIs) between computer servers separated by 50 mm spacing. Efficient ultrasonic linear piezoelectric motors (PMs) provide actuation with zero power required to hold the lens alignment. A four-channel FSOI is demonstrated with 1 \times 4 \text{ vertical cavity surface-emitting laser (VCSEL)} and photodiode (PD) arrays capable of 10 Gb/s transmission bandwidth. Demonstrated minimum step size of 1.68 \( \mu \text{m} \) is sufficient for aligning the 20 \( \mu \text{m} \) VCSEL spots onto the 40 \( \mu \text{m} \) PD receivers. Force transmission between PMs and a silicon MEMS flexure stage is accomplished using a 1-mm steel ball bearing in a magnetic groove, providing compliance in the nondriven axis. The ball-coupling design has 15 \( \mu \text{m} \) backlash and induces a maximum of 8 \( \mu \text{m} \) of cross-axis motion.

Index Terms—Alignment stage, microelectromechanical systems (MEMS), optical interconnect, piezoelectric ultrasonic stepper motor, two-axis actuator.

I. INTRODUCTION

Bandwidth capacity and high power consumption are fundamental limitations of the traditional copper-wire-based communication in computer servers. At very high bandwidths, optical interconnects will require less power to operate than copper data paths [1]. Optical interconnects are already widely used at the cabinet level in data centers and are promising candidates for on-chip interconnects in future microprocessors [2]. Here, we consider the problem of creating free-space optical interconnect (FSOI) at the board-to-board level. In comparison to interconnects using on-board waveguides routed to an optical plane, FSOI offers the advantages of high density [3] and lower board and backplane cost, but requires active multi-axis alignment to achieve efficient optical coupling from source to receiver [4]. The causes of source–receiver misalignment include vibration, thermal shifts, and static misalignment between the two server boards. Experimental measurements of a typical server chassis [5] show static misalignment (\( \sim 250 \mu \text{m} \)) is considerably greater than thermal shift (\( \sim 20 \mu \text{m} \) upon powering on the server) or mechanical vibration (\(< 1 \mu \text{m}\)). As a result, continuous dynamic correction is not required; instead, the ideal alignment system would correct the alignment once (upon installation or replacement of the server), after which the alignment would be retained with zero power consumption.

Earlier approaches to alignment systems for board-to-board FSOI have included bulk prisms [6], beam splitters [7], mechanical translation stages [8], liquid crystal beam steering [9], and optical microelectromechanical systems (MEMS) devices [10]. Among these, optical MEMS technology is attractive because it allows wafer-scale batch fabrication of low-cost devices. Many existing two-axis MEMS lens scanner designs require constant power to maintain lens position [11], have a limited correction range [12], or have a relatively small lens diameter [13], making them incapable of aligning an array of lasers over the 50-mm distance separating two boards in a modern server chassis.

Here, we describe a MEMS-based low-power active alignment system for FSOI using a piezoelectrically actuated lens to align vertical cavity surface-emitting laser (VCSEL) arrays to receiver photodiodes (PDs). The piezoelectric stepper motor technology used here consumes less than 250 mW in full-power operation and requires zero power to maintain static alignment. Similar to recent MEMS stepper motor designs [14], [15]. Unlike many earlier MEMS lens alignment systems, the bulk micromachined stage described here is suitable for positioning a large 6.35-mm-diameter lens, allowing the alignment of 1 \times 4 \text{ VCSEL} arrays over a 50-mm link distance.

II. DESIGN

A. Device and Test Setup

The lens aligner is a 1.3 cm \( \times 3.3 \times 3.3 \text{ cm} \) assembly of a silicon MEMS flexure stage, a plastic aspheric lens, and two piezoelectric motors (PMs), as shown in Fig. 1. The spacing and alignment of the flexure stage and PMs is provided by an aluminum mounting block. Force is transmitted between the MEMS flexure and PMs by a ball/groove device, which decouples the two translation axes, as described in Section II-D.

The board-to-board schematic is shown in Fig. 2. The MEMS aligner translates the first lens of a telecentric lens pair to position VCSEL beams to the PD array. The position information from the PD array is used for feedback control. The telecentric lens configuration reduces distortion and sensitivity to axial misalignment and board-to-board spacing variation [16]–[18].

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**Fig. 1.** Assembly schematic for complete two-axis lens aligner including monolithic mount, PMs and ball/groove couplers, MEMS flexure stage, aspheric lens, and PC Board.

**Fig. 2.** Test setup to demonstrate feedback control of the MEMS/FSOI alignment correction device. The primary components are VCSEL source, MEMS lens aligner, receiver lens, and PD array.

**B. Piezoelectric Stepper Motor Characterization**

Ultrasonic PMs are ideal for MEMS actuation due to their high driving force, large stroke, small incremental motion, and low power requirements [19]. The PMs used here (PI-652, Physik Instrumente) are 9 mm × 5.4 mm linear motors with 3-mm actuation range and minimum step size less than 1 mm. The PM has a maximum actuating force of 0.1 N and a frictional hold force of 0.2 N when not driven. The PM consists of a moving carriage/slider mounted on a resonating piezoelectric stator, as shown in Fig. 3. Electrodes on the two halves of the stator allow excitation at its resonant frequency (450 kHz), causing the carriage to travel toward the right or left, depending on which electrode is driven. The duration of the sinusoidal excitation signal is gated using a TTL input pulse signal. As described later, the carriage actuation distance is a function of the duration and amplitude of excitation as well as the load and position on the stator.

To characterize the mechanical behavior of the PM, a laser Doppler vibrometer (LDV) was used to measure the time-dependent displacement of the stator edge in response to a 0.5-ms pulse input. As shown in Fig. 4(b), the steady-state vibration amplitude is reached 150 μs after the start of excitation, corresponding to a mechanical quality factor $Q \sim 100$. LDV measurements collected at varying supply voltages showed that the vibration amplitude scaled in proportion to the supply voltage. Carriage motion is small until the vibration is near the steady-state amplitude, thus the minimum excitation pulse is 0.1 ms. Measurements collected at a supply voltage of 3.4 V for 0.1, 0.2, and 0.3 ms excitation pulses showed a nearly linear dependence of the motion on the pulse duration, with a minimum step size of 1.68 μm, as shown in Fig. 4(a). Similarly, varying the supply voltage from 3.4 to 5 V for a constant 0.1 ms pulse duration resulted in a nearly linear increase in the minimum step size from 1.68 to 11 μm.

As a measure of the repeatability of positioning, Fig. 5 shows a return-to-home (RTH) test in which the PM was driven at the minimum step size for ten steps in each direction. Over

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**Fig. 3.** PM image showing the piezoelectric stator and steel carriage/slider. The stator operates in a resonant mode that incrementally moves the slider as little as ∼1 μm.

**Fig. 4.** (a) Step size as a function of drive pulse duration. (b) LDV measurement on oscilloscope of PM vibration during a drive cycle, showing ring up time ∼0.15 ms. The minimum drive pulse is 0.1 ms, during which time, the PM vibration never reaches full amplitude, but it is sufficient to cause slider motion.
where \( E_{Si} = 169 \text{ GPa} \) is Young’s modulus for single crystal silicon along the \((110)\) crystalline axes, while \( h, w, \) and \( L \) represent the height, width, and length of the individual flexure beams, respectively. Because a stiffness relationship similar to (1) holds for out-of-plane \((z\text{-axis})\) deflections, the ratio of the out-of-plane to in-plane stiffnesses is approximately given by \( (h/w)^2 \). The maximum value of \((h/w)^2\) for defect-free DRIE fabrication is 10:1, so for \( h = 300 \mu m \) wafer thickness, \( w = 50 \mu m \).

Given the maximum rated force for each PM is 0.1 N, the stiffness of the flexures should be no more than 400 N/m to allow a full-scale lens displacement of \( x_{max} = \pm 250 \mu m \) to compensate for static board-to-board misalignment [5]. At the same time, it is desirable to make the flexures as stiff as possible to increase the frequency of the first mechanical resonance. For the prototype devices presented here, flexure length \( L = 2 \text{ mm} \) was selected. Substituting this value into (1) yields \( k_{eq} = 684 \text{ N/m} \), allowing a maximum displacement of \( x_{max} = 146 \mu m \) assuming \( F_{max} = 0.1 \text{ N} \).

Experimental measurements of the flexure stiffness were performed by mounting the MEMS device on a vibration exciter and observing the motion of the inner and outer frames using an LDV. Swept sine measurements performed over a frequency range of 100 Hz to 1 kHz, as shown in Fig. 7, show the in-plane resonances of the inner \((y\text{-axis})\) and outer \((x\text{-axis})\) frames at 487 and 360 Hz, respectively, corresponding to stiffnesses of \( k_y = 254 \text{ N/m} \) and \( k_x = 279 \text{ N/m} \).

The fabricated flexures were overetched and undercut with flexure top width \( a = 27.5 \mu m \), and bottom width \( b = 16.0 \mu m \). \( I_z \) for a trapezoidal beam cross section is given by

\[
I_z = \frac{h(a + b)(a^2 + b^2)}{48}
\]

Substituting (3) in (1) gives \( k_{calc} = 279 \text{ N/m} \), in good agreement with the measured values.

**D. MEMS/PM Coupling Device**

Coupling the PM actuators and MEMS flexure stage requires a mechanism that transmits actuator force in the direction of motion but is compliant in the orthogonal direction. In surface micromachined MEMS devices, this coupling has been achieved...
by a pin-in-slot mechanism [15]. Here, the coupling relies on a precision steel ball bearing ($\Omega_{\text{ball}} = 1000 \pm 2.5 \mu m$) retained in a magnetic groove aligned perpendicular to the driven axis, as shown in Fig. 8. The inner and outer frames of the stage have a square opening ($l_{\text{side}} = 1005 \pm 5 \mu m$) to accommodate the steel balls.

Motion of the outer frame causes the inner frame ball to roll along the magnetic groove (and vice versa). Published data on the wear of silicon surfaces used to support ball bearings [21] suggest a high degree of reliability for the ball–silicon interface. The design is tolerant of translational misalignments between the PMs and the flexure stage, since each ball can be freely positioned during assembly. Two nonlinearities result from the design and are explored in the results section. First, clearance between the ball and the flexure opening results in a dead zone. Second, rotational misalignments between the PM coupler and the flexure stage result in cross-axis coupling.

III. RESULTS

A. FSOI Setup

Experiments characterized the optical and mechanical performance of the FSOI system consisting of a source and receiver board separated by 50 mm. The receiver board is a $1 \times 4$ GaAs PIN PD array with a fixed lens ($f = 12.1$ mm), while the source board is a $1 \times 4$ VCSEL array assembled on a printed circuit board beneath the MEMS lens aligner, as shown in Fig. 2. Images of the VCSEL and PD arrays, as shown in Fig. 9, show that both devices have a $250-\mu m$ pitch, while the active area of each PD is approximately $40 \mu m$.

Images of the VCSEL spots in the receiver focal plane were collected using a CMOS imager (ISG, LW5–5-1394) in place of the PD array. Proper alignment between the two lenses, the VCSEL array, and the camera was ensured by collecting images of the VCSELs operating below the lasing threshold. Below threshold, satellite beams are visible around the main emission lobe; these beams are clearly visible when proper focus is achieved, as shown in Fig. 10.

The lasing VCSEL beam profiles at the receiver plane with the lens aligner positioned such that the beams are near the center of the source lens are shown in Fig. 11. The full width at 10% of maximum intensity is approximately $20 \mu m$. Taken together with the $40 \mu m$ PD diameter, the 3 dB radial alignment tolerance of the system is $60 \mu m$, requiring a minimum step size of $42 \mu m$ on each axis.

As the lens is displaced by the aligner, the focused spots show distortion due to off-axis aberrations in the lens. Fig. 12 is a composite image of the VCSEL array in four positions separated by $250 \mu m$. The spot at the lower right shows the maximum distortion and is located $\sim 500 \mu m$ from the lens center, representative of the position of the spot with the lens aligner driven to its maximum travel in both axes. To avoid saturating the camera, VCSEL images were collected with an aperture and neutral density filters between the source and receiver. Clipping on aperture drops the intensity of the lower right spot to $\sim 50\%$ of the intensity at lens center, but the beam width of the main
Fig. 12. Four-by-Four composite image of VCSEL beam distortion as a function of position relative to the telecentric lens pair centerline. The top inset (zoomed image of the spot in row 2, column 2) is the VCSEL beam closely aligned with the optical axis; the bottom inset (row 4, column 4) shows the distortion and loss of intensity for a spot ∼0.5 mm from the lens center due to aperture clipping.

Fig. 13. Eye diagrams taken at 2.5 Gb/s data rate at zero offset optical alignment and 250 μm offset show negligible performance difference.

Fig. 14. Composite image of a single VCSEL spot showing the limits of travel for the MEMS lens aligner.

Fig. 15. Stage motion over full range of travel. The dashed line shows the step size predicted based on the net force on the flexure stage. Step size near the backlash region is ∼2.2 μm.

B. Lens Aligner Performance

Lens aligner performance was characterized in the FSOI setup with the PMs driven with 0.1 ms pulses to achieve the minimum step size. Fig. 14 shows overlaid images of a single VCSEL spot translated by lens actuation to the extreme corners of the MEMS/PM range. Lens motion is 1:1 with image motion on the target due to the telecentric lens design. The observed limits of travel, ±110 μm in the x-axis and ±130 μm in the y-axis, are consistent with a maximum PM output force of 31 and 33 mN, roughly 1/3 the manufacturer value.

The variation of the step size over the full actuation range was measured by first driving the stage to extreme limit of travel, and then, stepping the lens to the opposite limit, while tracking the centroid of the VCSEL spot following each step command, as shown in Fig. 15. The observed behavior is approximated with a model in which the step size Δ is proportional to the net force acting on the stage

$$\Delta = \delta (F_{\text{max}} - k_x x)$$

where δ is a constant of proportionality and is equal to 48 mm/N for the inner axis. The PMs have nonuniform force characteristics across the full range, with less force available when operating near full stroke. The outer axis PM operates near full stroke resulting in a much lower proportionality constant d = 8 mm/N. At the initiation of motion, the forces from the PM and the flexures are additive and the largest step size (12 μm) is observed, whereas the step size diminishes to a value below 100 nm at the opposite extreme of travel. It was observed that the position of the PM slider on the stator affects δ. One consequence of this fact is that the displacement range is asymmetric, since the slider is not centered on the stator when the flexure stage is at zero deflection.

The backlash region of stage motion is observable in Fig. 15 when the stage reaches zero deflection. The size of the region is calculated as the product of the slope adjacent to the backlash (flat region) with the number of steps in the backlash region. For the inner axis, the backlash is calculated as 15.4 μm, while...
the outer axis backlash is similarly calculated to be 14.9 μm. Based on known variations in ball diameters and fabrication variations across the MEMS wafer, the expected backlash is 12.5 μm. Measured backlash is somewhat larger than expected due to overetch during fabrication.

Cross-axis coupling was measured by collecting centroid position of a single VCSEL beam incident on the CMOS camera for sweeps across the lens aligner’s range in both axes. The centroid sweeps are shown in Fig. 16. Inner axis motion is fairly linear and free from cross-axis coupling but outer axis motion has clear nonlinearities and exhibits up to 8 μm of cross-axis motion.

The nonlinearity results from the system geometry and magnet/ball interaction as the inner axis ball/groove coupling travels in its compliant axis. Fig. 17 shows how the cross-axis coupling is introduced to the system. As the outer axis moves, the ball rolls in the inner axis groove. Micrometer scale imperfections in the groove surface impede the motion of the ball, altering its position within the square opening of the MEMS stage. The effect of these defects is fairly repeatable as the outer axis motion is cycled backward and forward, as shown in Fig. 16.

IV. Conclusion

A MEMS lens aligner was described that allows a 6.35-mm diameter, f = 12.1 mm lens to be positioned in two axes over a 260 μm × 220 μm range, a range that allows compensation of static and thermal misalignments between two boards. The low-cost plastic optics used are suitable for a FSIO between two computer servers separated by 50 mm. The PM actuators used require zero input power to maintain the alignment. The largest step size, observed near the limits of travel, was 12 μm, approximately four times smaller than required to align the 20 μm VCSEL spot within the 40 μm high-speed PDs used here. Measurements of the step size versus displacement suggest that submicrometer step size could be reliably achieved by increasing the stiffness of the silicon flexures, at the cost of reducing the range of travel. Neglecting losses due to reflections from the surfaces of the nonantireflection coated lenses, a maximum intensity loss of 6% was observed for a laser spot positioned 500 μm from the center of the lens, representing the worst case for a spot deflected to the maximum limits of travel. The ball-coupling system used here showed repeatable behavior and a relatively small (15 μm) backlash region near the center of travel. Improved finishing of the ball-groove would reduce the 8 μm cross-axis coupling observed here.

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References


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Prof. Horsley is a recipient of the National Science Foundation CAREER Award and the UC Davis College of Engineering’s Outstanding Junior Faculty Award.
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Q2. Author: Please provide the year in which Shih-Yuan Wang became “Fellow member” of the IEEE.
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II. DESIGN

A. Device and Test Setup

The lens aligner is a 1.3 cm × 3.3 cm × 3.3 cm assembly of a silicon MEMS flexure stage, a plastic aspheric lens, and two piezoelectric motors (PMs), as shown in Fig. 1. The spacing and alignment of the flexure stage and PMs is provided by an aluminum mounting block. Force is transmitted between the MEMS flexure and PMs by a ball/groove device, which decouples the two translation axes, as described in Section II-D.

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As a measure of the repeatability of positioning, Fig. 5 shows a return-to-home (RTH) test in which the PM was driven at the minimum step size for ten steps in each direction. Over
Fig. 5. Drift in position of PM rotor over 20 identically driven RTH tests (ten minimum size steps in each direction) is larger than the minimum step distance. Measurements taken with unloaded PM (no MEMS flexure).

C. MEMS Flexure Stage

The MEMS flexure stage, as shown in Fig. 6(b), is composed of an inner frame, which provides y-axis movement, and an outer frame, which provides x-axis movement. The 20 mm × 20 mm device is fabricated from a 300-μm thick (100) Si wafer using a single-mask bulk micromachining process based on deep-reactive-ion etching (DRIE) through the entire wafer thickness. A plastic aspheric lens with focal length 12.1 mm, clear aperture of 4.4 mm, diameter of 6.35 mm, and mass 50 mg is affixed to the inner frame of the stage.

The flexures are compliant in-plane and stiff out-of-plane. To avoid introducing misalignment from lens vibration, the stage is designed to have low sensitivity to vibrations (due to cooling fans, hard-drives, etc.) up to ∼1 kHz. While in-plane stiffness of the stage is determined primarily by coupling with the PMs, out-of-plane stiffness is determined by the silicon flexures design. A folded flexure design is used, as shown in Fig. 6(a), to avoid nonlinear stiffening over a large (> 100 μm) displacement range while maintaining a high cross-axis stiffness ratio [20]. The stiffness of the folded flexure suspension is given by

\[
k_{eq} = \frac{48E_{\text{Si}}I_z}{L^3} \quad (1)
\]

\[
I_z = \frac{hw^3}{12} \quad (2)
\]

where \(E_{\text{Si}} = 169 \text{ GPa}\) is Young’s modulus for single crystal silicon along the (110) crystalline axes, while \(h\), \(w\), and \(L\) represent the height, width, and length of the individual flexure beams, respectively. Because a stiffness relationship similar to (1) holds for out-of-plane (z-axis) deflections, the ratio of the out-of-plane to in-plane stiffnesses is approximately given by \((h/w)^2\). The maximum value of \((h/w)\) for defect-free DRIE fabrication is 10:1, so for \(h = 300 \mu m\) wafer thickness, \(w = 30 \mu m\).

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Coupling the PM actuators and MEMS flexure stage requires a mechanism that transmits actuator force in the direction of motion but is compliant in the orthogonal direction. In surface micromachined MEMS devices, this coupling has been achieved
by a pin-in-slot mechanism [15]. Here, the coupling relies on a precision steel ball bearing \((\Omega_{\text{ball}} = 1000 \pm 2.5 \, \mu\text{m})\) retained in a magnetic groove aligned perpendicular to the driven axis, as shown in Fig. 8. The inner and outer frames of the stage have a square opening \((l_{\text{side}} = 1005 \pm 5 \, \mu\text{m})\) to accommodate the steel balls.

Motion of the outer frame causes the inner frame ball to roll along the magnetic groove (and vice versa). Published data on the wear of silicon surfaces used to support ball bearings [21] suggest a high degree of reliability for the ball–silicon interface. The design is tolerant of translational misalignments between the PMs and the flexure stage, since each ball can be freely positioned during assembly. Two nonlinearities result from the design and are explored in the results section. First, clearance between the ball and the flexure opening results in a dead zone. Second, rotational misalignments between the PM coupler and the flexure stage result in cross-axis coupling.

III. RESULTS

A. FSOI Setup

Experiments characterized the optical and mechanical performance of the FSOI system consisting of a source and receiver board separated by 50 mm. The receiver board is a 1 × 4 GaAs PIN PD array with a fixed lens \((f = 12.1 \, \text{mm})\), while the source board is a 1 × 4 VCSEL array assembled on a printed circuit board beneath the MEMS lens aligner, as shown in Fig. 2. Images of the VCSEL and PD arrays, as shown in Fig. 9, show that both devices have a 250-\(\mu\text{m}\) pitch, while the active area of each PD is approximately 40 \(\mu\text{m}\).

Images of the VCSEL spots in the receiver focal plane were collected using a CMOS imager (ISG, LW5–5-1394) in place of the PD array. Proper alignment between the two lenses, the VCSEL array, and the camera was ensured by collecting images of the VCSELs operating below the lasing threshold. Below threshold, satellite beams are visible around the main emission lobe; these beams are clearly visible when proper focus is achieved, as shown in Fig. 10.

The lasing VCSEL beam profiles at the receiver plane with the lens aligner positioned such that the beams are near the center of the source lens are shown in Fig. 11. The full width at 10\% of maximum intensity is approximately 20 \(\mu\text{m}\). Taken together with the 40 \(\mu\text{m}\) PD diameter, the 3 dB radial alignment tolerance of the system is 60 \(\mu\text{m}\), requiring a minimum step size of 42 \(\mu\text{m}\) on each axis.

As the lens is displaced by the aligner, the focused spots show distortion due to off-axis aberrations in the lens. Fig. 12 is a composite image of the VCSEL array in four positions separated by 250 \(\mu\text{m}\). The spot at the lower right shows the maximum distortion and is located \(\sim 500 \, \mu\text{m}\) from the lens center, representative of the position of the spot with the lens aligner driven to its maximum travel in both axes. To avoid saturating the camera, VCSEL images were collected with an aperture and neutral density filters between the source and receiver. Clipping on aperture drops the intensity of the lower right spot to \(\sim 50\%\) of the intensity at lens center, but the beam width of the main
Fig. 12. Four-by-Four composite image of VCSEL beam distortion as a function of position relative to the telecentric lens pair centerline. The top inset (zoomed image of the spot in row 2, column 2) is the VCSEL beam closely aligned with the optical axis; the bottom inset (row 4, column 4) shows the distortion and loss of intensity for a spot ∼0.5 mm from the lens center due to aperture clipping.

Fig. 13. Eye diagrams taken at 2.5 Gb/s data rate at zero offset optical alignment and 250 μm offset show negligible performance difference.

lobe is similar to undistorted beam width. Measurements collected with the PD array (without an aperture) showed the peak spot intensity varied by less than 6% over a 2.5-mm translation range. Eye diagrams at 2.5 Gb/s data transmission rate, as shown in Fig. 13, have negligible change in quality for a lens translation of 250 μm, or the full capability of the system. The eye diagrams are taken without any aperture in the beam path. Four parallel 2.5 Gb/s channels provide for 10 Gb/s communication.

B. Lens Aligner Performance

Lens aligner performance was characterized in the FSOI setup with the PMs driven with 0.1 ms pulses to achieve the minimum step size. Fig. 14 shows overlaid images of a single VCSEL spot translated by lens actuation to the extreme corners of the MEMS/PM range. Lens motion is 1:1 with image motion on the target due to the telecentric lens design. The observed limits of travel, ±110 μm in the x-axis and ±130 μm in the y-axis, are consistent with a maximum PM output force of 31 and 33 mN, roughly 1/3 the manufacturer value.

The variation of the step size over the full actuation range was measured by first driving the stage to extreme limit of travel, and then, stepping the lens to the opposite limit, while tracking the centroid of the VCSEL spot following each step command, as shown in Fig. 15. The observed behavior is approximated with a model in which the step size \( \Delta \) is proportional to the net force acting on the stage

\[
\Delta = \delta (F_{\text{max}} - k_x x)
\]

where \( \delta \) is a constant of proportionality and is equal to 48 mm/N for the inner axis. The PMs have nonuniform force characteristics across the full range, with less force available when operating near full stroke. The outer axis PM operates near full stroke resulting in a much lower proportionality constant \( d = 8 \) mm/N. At the initiation of motion, the forces from the PM and the flexures are additive and the largest step size (12 μm) is observed, whereas the step size diminishes to a value below 100 nm at the opposite extreme of travel. It was observed that the position of the PM slider on the stator affects \( \delta \). One consequence of this fact is that the displacement range is asymmetric, since the slider is not centered on the stator when the flexure stage is at zero deflection.

The backlash region of stage motion is observable in Fig. 15 when the stage reaches zero deflection. The size of the region is calculated as the product of the slope adjacent to the backlash (flat region) with the number of steps in the backlash region. For the inner axis, the backlash is calculated as 15.4 μm, while...
linear and free from cross-axis coupling but outer axis motion has clear nonlinearities and exhibits up to 8 μm of cross-axis motion.

The nonlinearity results from the system geometry and magnet/ball interaction as the inner axis ball/groove coupling travels in its compliant axis. Fig. 17 shows how the cross-axis coupling is introduced to the system. As the outer axis moves, the ball rolls in the inner axis groove. Micrometer scale imperfections in the groove surface impede the motion of the ball, altering its position within the square opening of the MEMS stage. The effect of these defects is fairly repeatable as the outer axis motion is cycled backward and forward, as shown in Fig. 16.

IV. CONCLUSION

A MEMS lens aligner was described that allows a 6.35-mm diameter, \( f = 12.1 \ mm \) lens to be positioned in two axes over a 260 μm × 220 μm range, a range that allows compensation of static and thermal misalignments between two boards. The low-cost plastic optics used are suitable for a FS0I between two computer servers separated by 50 mm. The PM actuators used require zero input power to maintain the alignment. The largest step size, observed near the limits of travel, was 12 μm, approximately four times smaller than required to align the 20 μm VCSEL spot within the 40 μm high-speed PDs used here. Measurements of the step size versus displacement suggest that submicrometer step size could be reliably achieved by increasing the stiffness of the silicon flexures, at the cost of reducing the range of travel. Neglecting losses due to reflections from the surfaces of the nonantireflection coated lenses, a maximum intensity loss of 6% was observed for a laser spot positioned 500 μm from the center of the lens, representing the worst case for a spot deflected to the maximum limits of travel. The ball-coupling system used here showed repeatable behavior and a relatively small (15 μm) backlash region near the center of travel. Improved finishing of the ball-groove would reduce the 8 μm cross-axis coupling observed here.

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