A DRIE COMB-DRIVE ACTUATOR WITH LARGE, STABLE DEFLECTION RANGE FOR USE AS AN OPTICAL SHUTTER

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ABSTRACT

A comb-drive actuator has been developed with new features that increase the static deflection range to 175 um without sacrificing die area or switching speed. An optical shutter for a tunable laser has been made by attaching a large-deflection actuator and mirror to opposite ends of a pivoting lever. A 2.5:1 lever ratio allows the smaller mass of the mirror to balance the relatively large actuator mass to reduce vibration sensitivity. The shutter routinely achieves over 50 dB attenuation in production laser modules, with a switching speed of less than 1 ms. A bidirectional actuator with similar design features has 350 um of total travel with less than 3% nonlinearity.

INTRODUCTION

Optical attenuators are often used as power management elements in an optical network. Dynamic gain equalization and power attenuation are the most common applications. In a tunable laser product, such as the one manufactured by Iolon Corporation, a power-blocking element is needed during channel switching [1]. The optical attenuator is used as a binary shutter to completely block the output laser beam as the wavelength is tuned from one channel to another during switching. This helps to prevent undesired intermediate wavelengths from being launched into the output fiber, while maintaining fast switching speeds and accurate channel locking. A robust tunable laser with acceptable tuning speed characteristics requires a shutter with at least 40 dB of attenuation within 1 ms.

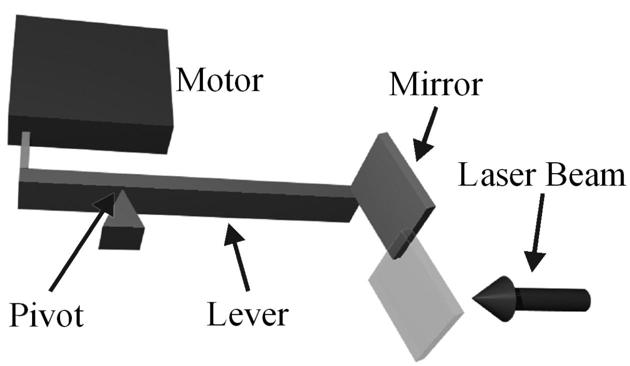

Figure 1. Schematic diagram of a micromachined shutter showing the linear motor, mirror, pivot point, lever arm, and incident laser beam.

The laser's free-space output beam has a $1/e^2$ diameter of 160 um, so shutter travel exceeding 315 um is needed to achieve the required attenuation. In practice, a deflection range exceeding 400 um is required to allow for passive placement in the manufacturing process and to take into account beam alignment tolerances. Due to geometric constraints within the laser butterfly package, the shutter mirror must extend off the edge of the chip, and shutter designs that span both sides of the collimated beam are not feasible.

One shutter design solution uses a linear actuator that is coupled by a lever to an externally fabricated 600 × 500 um mirror. The actuator rotates the lever, causing the mirror to intercept the incident laser beam. This design is shown schematically in Figure 1.

ACTUATOR DESIGN

The stable deflection ranges of conventional comb drive actuators have been limited due to electromechanical instability occurring when the electrostatic forces between the sides of the combs overwhelm the suspension stiffness perpendicular to the actuation direction. Side instability is exacerbated in comb drive actuators because the side stiffness of traditional folded-flexure suspensions drops with large forward deflections [2-4]. In earlier work, improved folded-flexure designs were used to produce deflections of 110 um [5-7], but significantly larger deflections are required for the shutter application.

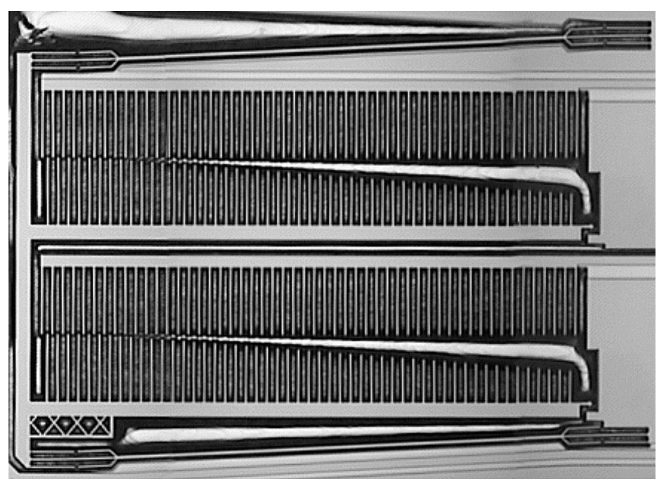

Figure 2. Microscope photograph showing a shutter actuator with a range of 175 um.

To achieve the deflections required for the shutter application, the side-to-forward stiffness ratio of the actuator suspension must be greatly increased. In the comb-drive

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actuator in Figure 2, the folded-flexure has been eliminated and replaced by a pair of single-beam flexures with bossed central sections – effectively turning the suspension into a flexural 4-bar linkage. Finite element analyses indicate that for this actuator the bossed sections increase the side stiffness of the suspension beams by a factor of 1.8 compared to unbossed suspension beams with equivalent forward stiffness. While the stiffness ratio of a folded flexure drops with the square of the forward deflection, the stiffness ratio of a single-beam flexure is essentially independent of deflection. Because the stiffness ratio remains high, increased deflections are possible.

The new suspension brings challenges as well as benefits. Folded-flexure suspensions have been used in comb-drive actuators because the shuttle moves in a nearly straight line in the forward direction, minimizing the side electrostatic forces. In contrast, the straight-beam suspension causes the shuttle to move along a shallow arc. The impact of the resulting side displacements can be minimized by redesigning the comb teeth. For single-direction actuation, the displacements may also be reduced by fabricating the suspension in an initially deflected position.

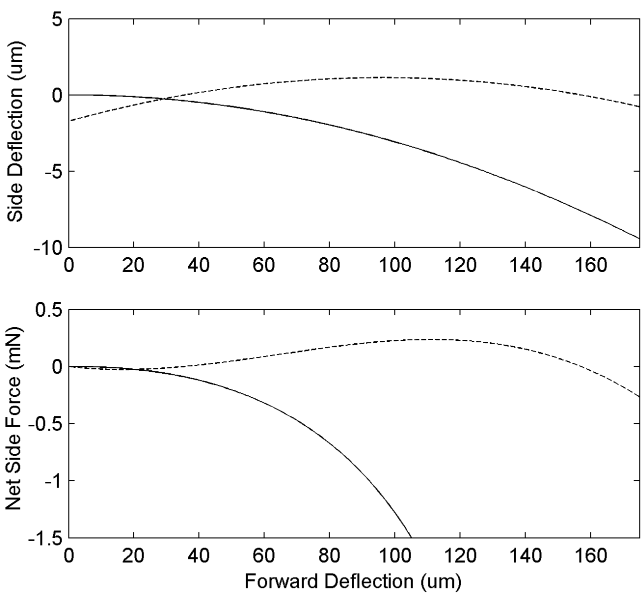

Figure 3. Top: Calculated comb side deflection. Bottom: Calculated side electrostatic force. In both graphs, the solid curve is for straight combs and suspensions while the dotted curve represents offset and inclined combs with pre-deflected suspensions.

The actuator in Figure 2 is only actuated in one direction, so its suspension is fabricated in a position corresponding to -85 um deflection. To further counteract the nonlinear comb trajectory and minimize the imbalance in side electrostatic forces, the comb teeth are inclined 0.4 degrees relative to the forward direction, and the moving combs are offset 0.5 um in the side direction [8]. Mechanical stops limit the actuator range to 175 um. Figure 3 compares the comb trajectory and side electrostatic force of an actuator with straight combs and suspensions to the final, optimized design.

FABRICATION

The fabrication process of the shutter actuators is identical to that of the optical switch and tunable laser actuators described previously [5]. Essentially, an 85 um single-crystal silicon layer with a buried cavity is DRIE etched to form the suspended electrostatic actuator.

All front-end wafer processing for the actuators and optical switches is carried out at GE NovaSensor, with a proprietary process [9] shown schematically in Figure 4.

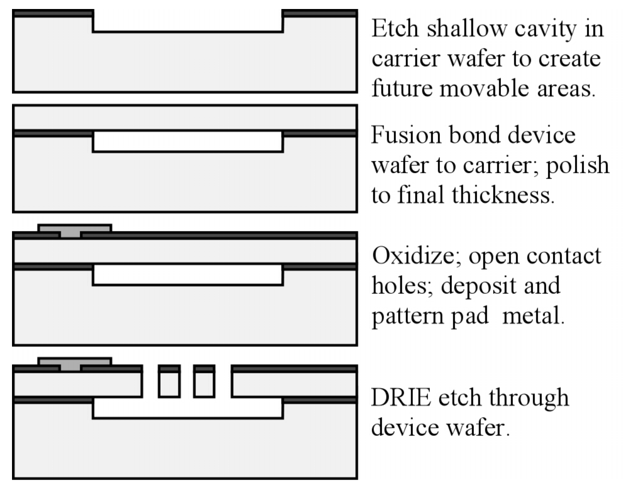

Figure 4. Schematic diagram showing the actuator fabrication process.

SHUTTER DESIGN AND PERFORMANCE

The actuator in Figure 2 may be modified to make an optical shutter. In Figure 5, two additional comb banks have been added to the actuator to improve performance and utilize the available die area. As in the schematic in Figure 1, the device has the mirror and actuator connected to opposite ends of a pivoting lever with a 2.5:1 lever-ratio. The lever allows the small mass of the mirror to balance the relatively large actuator mass, reducing vibration sensitivity by a factor of 40.

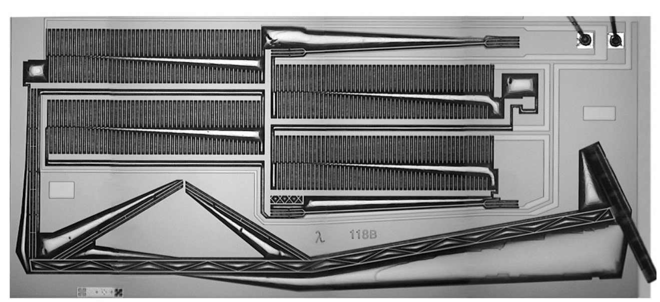

Figure 5. Microscope photograph showing a mechanically balanced shutter with a mirror travel of 425 um.

Figure 6 shows the measured quasi-static response of the balanced actuator shown in Figure 5. A 670 nm laser beam was reflected off the shutter mirror onto a position sensitive detector to measure deflection. The transfer function is highly nonlinear. Full actuator deflection was achieved with an applied voltage of 145 V.

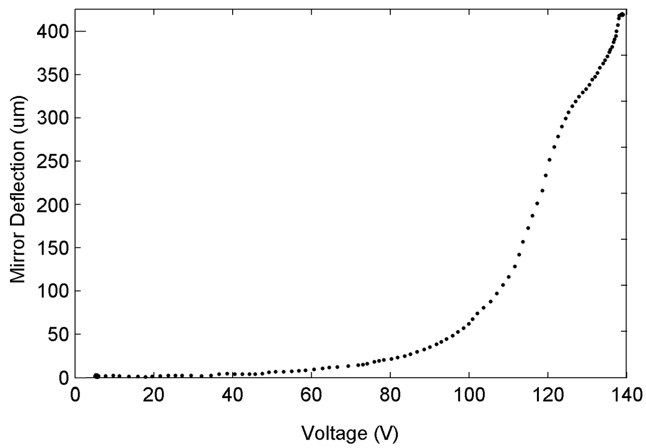

Figure 6. Measured quasi-static response of the balanced shutter actuator. Mechanical stops limited the mirror deflection range to 425 um.

To investigate the effect of the mechanically balanced design on vibration sensitivity, a laser was placed onto a mechanical shaker. In response to 1 G low-frequency vibrations, the actuator moved 0.04 um and the shutter mirror moved 0.1 um. This amount of mirror motion corresponds to a change of at most 0.04 dB of attenuation. Without the balancing lever, the actuator shown in Figure 2 moved 1.6 um/G, so the balanced design improved the vibration rejection by a factor of 40.

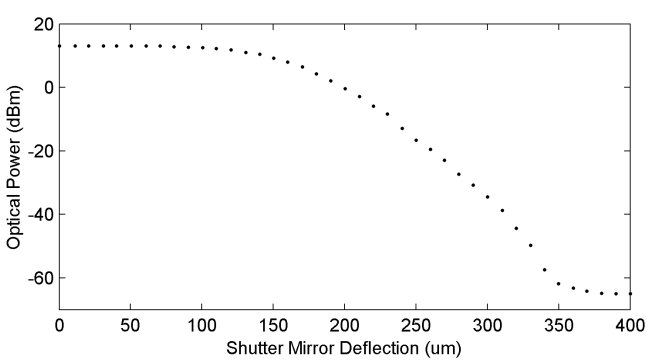

Figure 7. Measured optical attenuation of the shutter at 1550 nm wavelength as a function of shutter deflection with single-sided drive.

The mechanically balanced actuator routinely achieves over 50 dB attenuation in production laser modules with a switching speed of less than 1 ms. Figure 7 shows the optical attenuation as a function of the deflection of the shutter mirror, and Figure 8 shows the optical attenuation over time during a switching event.

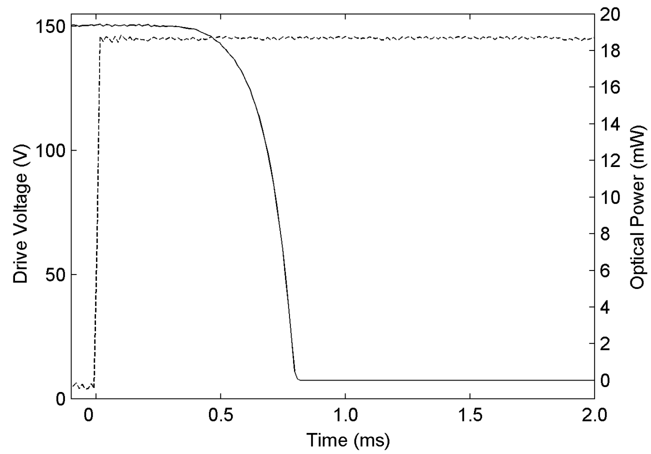

Figure 8. Drive voltage (dashed) and transmitted power (solid) for a shutter switching event. The actuator required 145V for full deflection and completely blocked the output beam in less than 1 ms.

BIDIRECTIONAL ACTUATOR DESIGN

Comb-drive actuators are often designed for bidirectional actuation. This doubles the total deflection range without impacting the side stability. Figure 9 shows a bidirectional actuator based on that used in the shutter. Because the combs face in opposite directions, the suspension cannot be fabricated in an initially deflected position. To counteract the nonlinear comb trajectory and minimize the imbalance in side electrostatic forces, the combs must be significantly inclined relative to the forward direction, and the moving combs must be offset in the side direction.

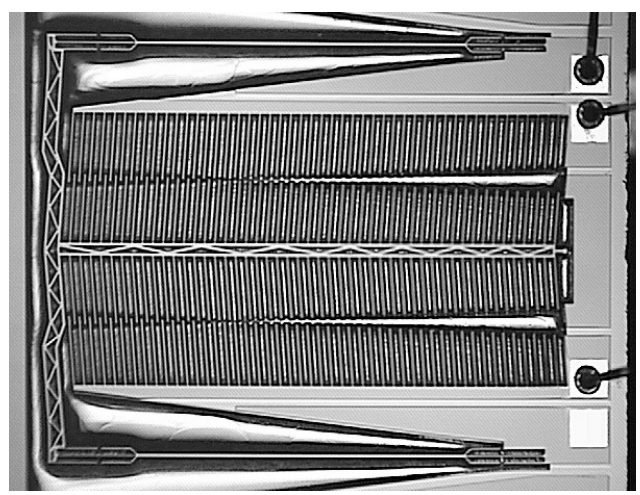

Figure 9. Photograph of a differential drive actuator with 350 um deflection range. The actuator occupies only 2.5 mm^2. An actuator with fully overlapping combs would require a 50% larger die and have twice the moving mass.

A push-pull design allows the actuator to be driven differentially, significantly improving the linearity of the quasi-static transfer function. However, perfect linearity requires that the combs overlap for all displacements [10]. For the shutter application, the actuator would need 350 um-long combs. A more area-efficient solution is to use combs designed to provide a displacement-dependent force term that counteracts the nonlinear V^2 dependence. In theory, non-prismatic comb teeth could be used [11], but a much simpler approach is to use combs of varied length, effectively making the number of active combs a function of deflection.

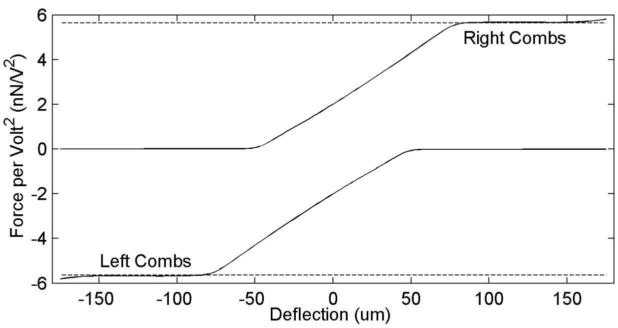

Figure 10. Calculated displacement dependence of the forward electrostatic force with the unequal comb lengths shown in Figure 9 (solid). For fully-overlapping combs the force would be independent of displacement (dashed).

The actuator in Figure 9, for example, has a deflection range of ±175 um and a predicted nonlinearity of 2%, but the longest comb is only 240 um, and the combs initially overlap by only 30 um. The calculated displacement dependence of the motive force is shown in Figure 10 for this actuator.

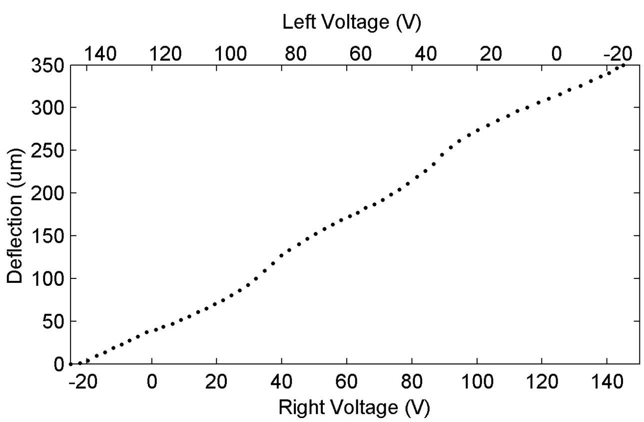

Figure 11. Measured quasi-static response of the actuator shown in Figure 9, which has the displacement dependent forces in Figure 10. The nonlinearity is less than 3%.

Figure 11 shows the measured quasi-static response of the example differential-drive actuator. The actuator had a fundamental resonant frequency of 490 Hz. The shuttle deflection was measured visually using an optical microscope with 1000× magnification. The nonlinearity of the transfer function was less than 3%, making the actuator a good candidate for a closed-loop, variable optical attenuator.

SUMMARY

A comb-drive actuator has been developed with new features that increase the stable deflection range to 175 um. An optical shutter for a tunable laser has been made by attaching a large-deflection actuator and mirror to opposite ends of a pivoting lever producing 425 um of mirror motion. The balanced, levered design reduces vibration sensitivity by a factor of 40. The shutter exhibits more than 40 dB of attenuation with a switching speed of less than 1 ms. A similar actuator in a push-pull configuration has 350 um of total travel with less than 3% nonlinearity.

ACKNOWLEDGEMENTS

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