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A new latched 2 × 2 optical switch using bi-directional movable electrothermal H-beam actuators☆

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Abstract

Combining a new H-beam actuator, movement link structure, reflective micro-mirror, and arched buckle spring to demonstrate a new compact latched 2 × 2 optical switch device is first reported. This novel H-beam actuator can generate bi-directional static displacement and bi-directional motion. Optical switch using this H-beam actuator is well functioned and exhibits good optical characteristics with industrial level performance. The measured optical switching characteristics include switching time of 5 ms under a 25 V dc pulse, back reflection loss of −52 dB, cross-talk of −60 dB, insertion loss of 0.8 dB, polarization-dependent loss of 0.03 dB, and wavelength-dependent loss of 0.11 dB.

Keywords: Electrothermal actuator; H-beam; Optical switch

1. Introduction

The electrothermal actuators have been known as their large displacement and high force output. Two well-studied electrothermal actuators are U-shaped actuator [1–4] and V-beam actuator [5,6]. Both actuators can provide one directional displacement in the static actuation operation. This characteristic is attributed by that static displacement generated from electrothermal actuators is formed by net volume expansion due to the thermal expansion difference distributed over the whole actuator structure. Since the net volume expansion is always pointing to one direction. The large static displacement and large force output are normally required in practical applications. In the case of optical switch, the latch function is required in which it means there is no electrical power needed to maintain device at either transmission or switching state. Thus, the two-way motion and bi-stable actuation is demanded for optical switch application. The buckled-beam spring of the arch-shaped leaf spring geometry driven by a bi-directional electrostatic comb actuator has been applied to the latched optical switch [7].

In our previous studies [8,9], we firstly reported the feasibility of cross-bar optical switch based on using a bi-directional movable reflective shutter driven by two separately located V-beam electrothermal actuators with opposite actuation directions, and using the buckle spring to bi-stably control the switch body. However, such designs lead to larger footprint of device, and they require two separately controlled actuator to perform the bi-directional strokes. To make a more compact device, we introduced a latched optical switch deploying a novel bi-directional movable H-beam actuator to drive reflective shutter via a link structure, and using buckle springs to perform the latch function.

2. Device configuration and fabrication

The large displacement and force output are main concerns to evaluate the performance of micro-actuators. Regarding

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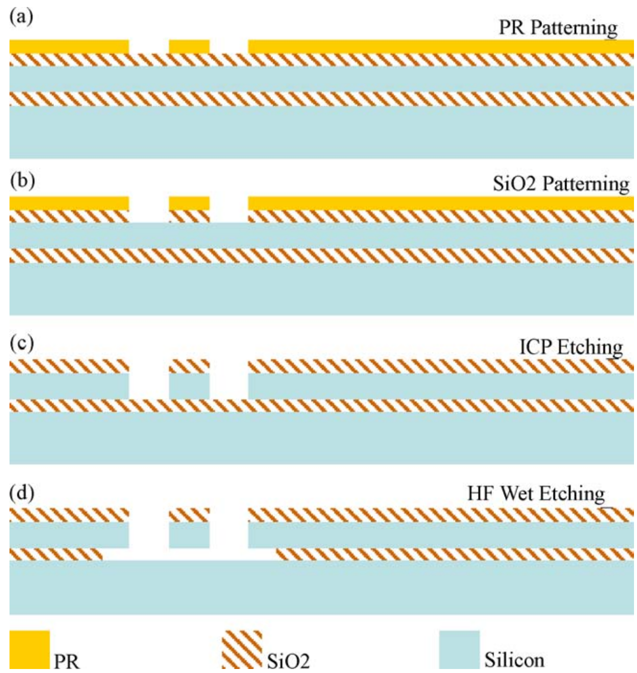

Fig. 1. (a–d) The schematic drawing of a SOI wafer regarding to cross-sectional view of H-beam optical switch device in the bulk micro-machining process flow.

to the application-specific technical requirements of optical switch, the capabilities of bi-directional two-way motion, i.e., bi-directional static displacement, and latch function are the crucial items. Latch function has been realized by using buckle springs [7–9], and by using micro-clampers [10]. Because the net thermal expansion normally contributes to one directional volume deflection, i.e., the static displacement, the electrothermal actuators like U-shaped actuator and V-beam actuator only generate one directional static displacement. Thus, the bi-directional two-way motion could not be realized based on traditional electrothermal actuators until now. Except the requirement of bi-directional static displacement, large force output and large static displacement are necessary for optical switch application. Unless adopting high driving voltage and appropriate design of electrostatic comb drive actuator [11,12], these technical requirements for optical switch could not be fulfilled by using electrostatic comb drive actuators.

We propose a new design of electrothermal actuator to meet the above-mentioned requirements. An H-shaped silicon beam actuator, denoted as the H-beam actuator, is constructed from the silicon-on-insulator (SOI) substrate via deep reactive ion etching (DRIE) bulk micro-machining processes as shown in Fig. 1. The silicon moving parts were subsequently released from the substrates using buffered HF solutions to remove the underneath SiO_2 layer of the SOI wafers. First, photoresist (PR) mask patterns of the device were made on the SOI wafers (Fig. 1a). The SiO_2 hard mask patterns were defined as same as the shape of the PR patterns by reactive ion etching (Fig. 1b). The PR on the processed SOI wafers was then removed using PR stripper. Fig. 1c shows that the SOI wafers were etched using deep reactive ion etch with patterned SiO_2 as an etching hard mask. The SOI wafers were etched through the entire silicon device layer using the buried oxide underneath as the etch stop. Finally, the silicon moving parts were subsequently released from the substrates using buffered HF solutions to remove the underneath SiO_2 layer of the SOI wafers (Fig. 1d). The SEM photos of the fabricated H-beam driven optical switch devices are shown in Fig. 2a–c, where the H-beam actuator is located on right-hand side of Fig. 2b. The dimension of this H-beam electrothermal actuator is 3000 μm in length and 10 μm in width. Fig. 2b also shows two buckle spring beams connected with the switch body beam to keep the switch body being suspended. The closed-up view of the movement link structure is shown in Fig. 2c. The movement link structure provides a clamped space to let the T-shaped arm of H-beam actuator can bidirectional movable inside the clamped space. Fig. 2d depicts the elements of the optical switch device driven by an H-beam actuator. When the electrical load is applied on one side of H-beam, this side beam becomes hot and deformed. In order to generate a net volume elongation along with a designed direction of said deformed beam, each side of H-beam has been designed to be a V-beam. Then, the deformed beam will pull the other beam, where there is no bias applied, to be deflected in the same direction. Once this un-biased beam is deformed due to such pulling force, the whole actuator structure will generate a net displacement in the direction along with the arched direction of the biased beam. The relative operation steps are depicted in Fig. 3a and b. Secondly, with respect to the other operation alternative, i.e., the operation steps as shown in Fig. 3c and d, we apply the electrical load on the former un-biased beam. Then, this side of beam turns to be the hot beam to trigger the actuation and to pull the other side beam. As a result, the whole actuator structure will generate the opposite directional displacement against to the previous operation case. Therefore, the bi-directional static displacement or stroke provided by H-beam actuator is realized.

In terms of the bi-stable optical switch functions, the transmission state (Fig. 3a and d) and switching state (Fig. 3b and c) of a 2 × 2 optical switch using the H-beam actuator and buckle springs are illustrated to demonstrate the operation of latched switching function. The ends of buckle spring beams on both sides of device are anchored on substrate. These two buckle springs support switch body to be suspended on substrate. The buckle spring is considered as an axially loaded deformed beam [14,15]. The force required to move the buckle spring from its initial rest position to its second bi-stable position is about two times larger than the force needed to push the buckle spring from its second bi-stable position back to its initial rest position [9,15]. Without a necessary enough force or energy to help the buckle spring itself to overcome the energy barrier to be deformed toward the opposite arched direction of its original arched shape, the buckle spring is stably maintained at its original arched shape.

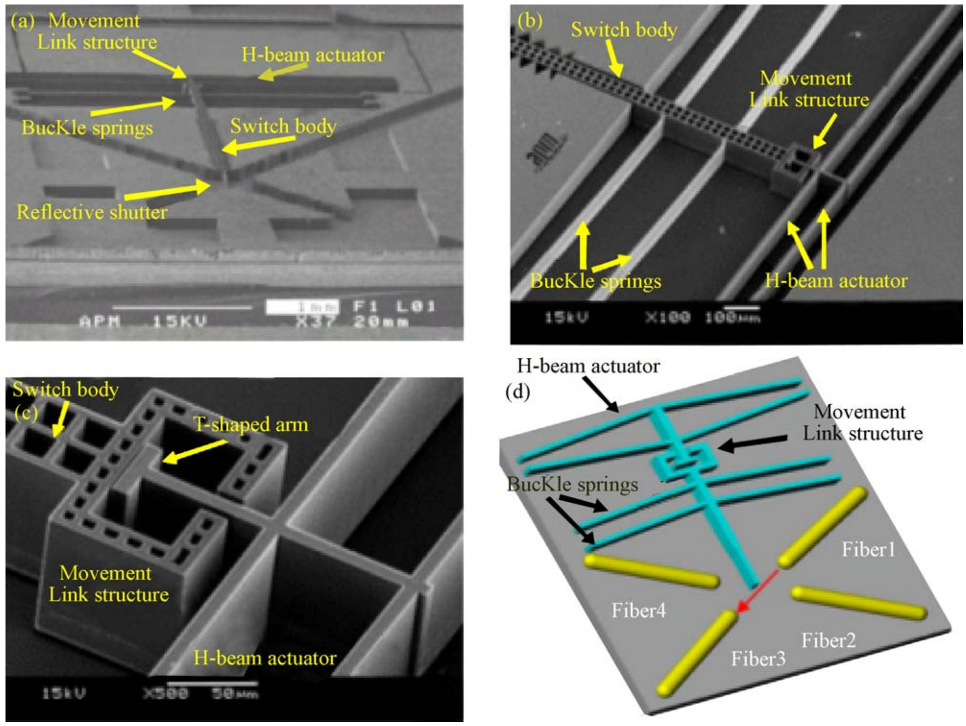

Fig. 2. The illustration of the H-beam optical switch device: (a) the SEM photo of the device; (b) the SEM photo of different view angle for optical switch as shown in (a); (c) the SEM photo of closed-up view of switch body, buckle springs and movement link structure of the H-beam optical switch; (d) device drawing.

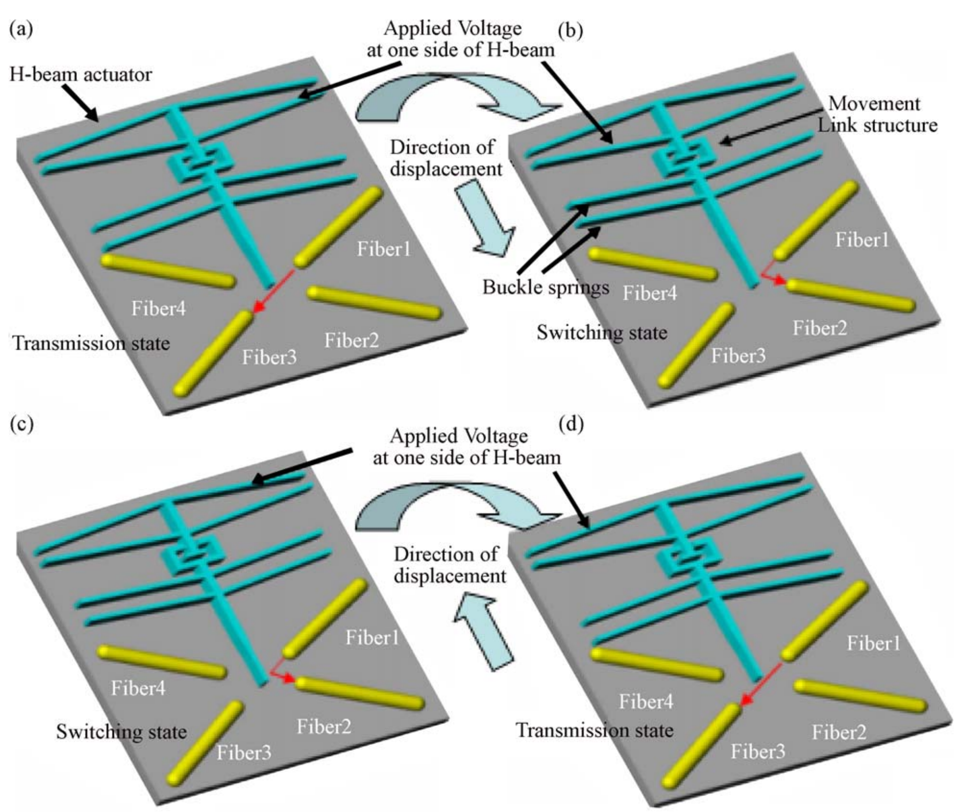

Fig. 3. Schematic drawings of H-beam driven optical switch in transmission states of (a and d), and in the switching states of (b and c). The reflective mirror connected with switch body is bi-stably staying at transmission and switching positions in which this behavior is controlled by the buckle springs and driven by bi-directional movable the H-beam electrothermal actuator.

When the electrical load is applied to H-beam actuator, where the arched direction of the biased beam is the same as the reflective shutter forward moving direction, this side beam structure will push the shutter and switch body beam forward moving from initial stable position (Fig. 3a) to the other stable position (Fig. 3b), thus the device will change its status from transmission state (Fig. 3a) to reflection state (switching state, i.e., Fig. 3b). The device can be changed from the second stable position (Fig. 3b or c) back to its initial stable position (Fig. 3d or a) by applying electrical load on opposite side of H-beam to pull back the switch body via movement link structure. The buckle springs can help the switch device to be maintained at either state without electrical power consumption. The on–off switching function is performed in this way.

3. Measured results and device characteristics

The maximum static displacement of H-beam is simulated by using finite element modeling (FEM). The static displacement generated by H-beam has to be larger than the distance between two bi-stable positions of optical switch. In other words, this distance has also to be larger than the diameter of optical light beam to let light signals being fully transmitted or reflected by the reflective micro-shutter. Moreover, the force generated by actuator has to be larger enough to push and move the buckle springs. Firstly, Fig. 4a shows the simulated data of maximum displacement of an H-beam actuator with 3000 μm length depending on various tilted angles and beam widths. According to different beam widths, the optimal tilted angle is located in between 0.2° and 0.6°. We can derive maximum displacements in the range of 80–150 μm for beam width reducing from 12 to 6 μm, respectively. Secondly, we need to consider the spring force output of deformed H-beam due to external applied electrical load. Fig. 4b shows the simulated curves of force output versus various combinations of tilted angles and actuator beam widths for H-beam actuators under 30 V dc electrical load. It illustrates that the thinner beam width is, the smaller force out will be. Because the thinner beam requires less electrical power to drive itself to a set static displacement, while the wider beam consumes more electrical power to generate the same set static displacement. The spring restoring energy regarding to the thinner beam at a determined static displacement will be less than the energy of the wider beam. Therefore, the output force of the thinner beam at a said static displacement is smaller accordingly. The H-beam actuator of 3000 μm beam length, 10 μm beam width, and 0.6° tilted angle is selected as the device of moderate design for practical characterization, since it can provide maximum displacement and maximum force output around 100 μm and 1000 μN, respectively. Referring to former data discussed in previous study [9,16,17], the force required to move the buckle spring is less than 500 μN for buckle springs with beam width and length of less than 3 μm and larger than 1250 μm, respectively. Thus, we consider optical switch using H-beam actuator and buckle springs of aforementioned dimensions can achieve the optical switching features properly.

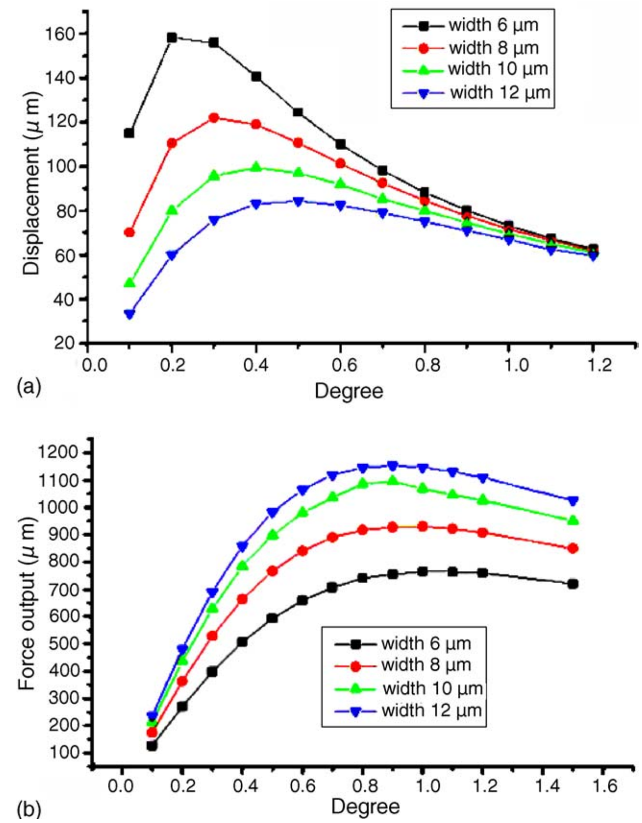

Fig. 4. (a) Simulated maximum displacement vs. tilted angle for an H-beam and (b) simulated maximum force output vs. tilted angle for an H-beam.

The measurement setup is illustrated in Fig. 5a. We placed four lens fibers onto the DRIE derived silicon trenches. We provided the optical signal of 1550 nm wavelength from one input port, and measured the optical signal from one of two output ports. The received optical power is converted into electrical voltage signal via an O–E converter, and the signals are recorded by an oscilloscope. The CCD images of optical switch device with four aligned lens fibers are shown in Fig. 5b. The operation of switch from transmission state to switching state is demonstrated by using closed-up views taken by CCD which are shown in Fig. 6. Fig. 6a shows the denotation of elements of the device, and the device is remained at its first stable state without electrical biasing. At the beginning, we applied a dc pulse of 25 V on the left side beam of H-beam actuator of said device. This left side beam became hot and deformed so as to push the buckle springs moving from its first stable position as shown in Fig. 6a to second stable position as shown in Fig. 6b. Comparing the positions of buckle springs in Fig. 6a and b, we can clearly identify the deformed curve shape of buckle springs is opposite to each other. These positions are referred to the bi-stable positions for latch function of bi-stable buckle springs. Thereafter, we applied a dc pulse of 25 V on the right side beam of

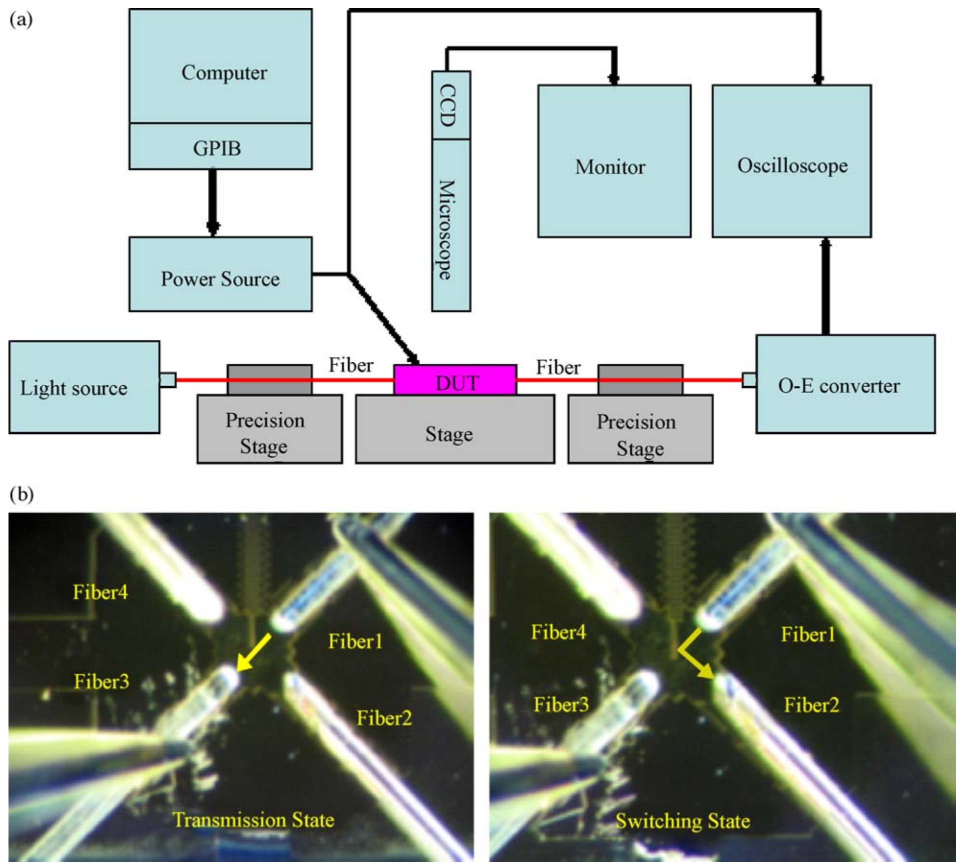

Fig. 5. (a) The experimental setup of optical switching characteristics measurement and (b) the CCD image of arranged and aligned optical switch device using an H-beam actuator under its transmission state (left side) and switching state (right side).

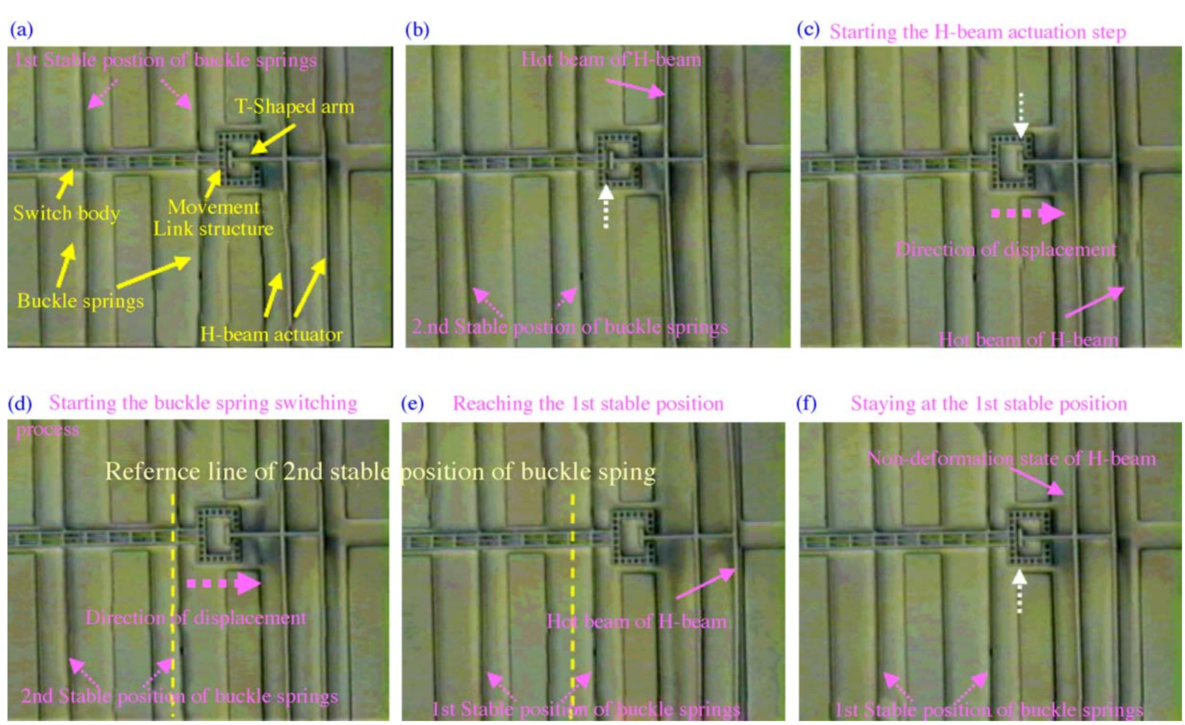

Fig. 6. (a–f) Captured motion images regarding to the switching mechanism during operation of latched optical switch.

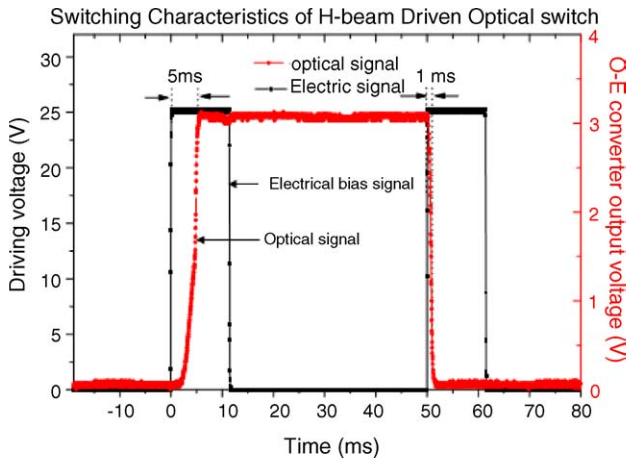

Fig. 7. Switching speed of made optical switch devices between two bi-stable positions under different driving conditions.

H-beam actuator of said device. This left side beam became hot and deformed toward right-hand side. This left side hot beam could drive the whole H-beam structure deformed and generated a displacement as shown in Fig. 6c. Meanwhile, the T-shaped arm of H-beam actuator is moved from left side to right side within the clamped space of the movement link structure, as comparing Fig. 6c and b. The left and right side positions of T-shaped arm are denoted by the dotted white arrow mark. When we maintained the applied voltage, the T-shaped arm started to push the right side of the movement link structure to trigger the buckle spring switching step as shown in Fig. 6d, while the arched shape of buckle spring is changed after the switching step as shown in Fig. 6e. This switching action from Fig. 6d and e is governed by the buckle spring itself instead of H-beam actuator. The position of buckle springs has been moved from first stable position to second stable position. The reference dot line shown in Fig. 6d and e is used to illustrate the distance between two stable positions of buckle spring. After switching step, we removed the applied voltage from right side beam of H-beam. The H-beam actuator remained at its un-bias state as shown in Fig. 6f. In other words, Fig. 6f presents the rest state of switch device as same as the state of Fig. 6a in which it means its first stable position without applying electrical to keep its status. It shows the feasibility of combining the H-beam actuator, buckle beam spring and movement link structure to achieve bi-directional stroke and latch function.

As shown in Fig. 7, the measured switching time of forward moving is 5 ms under a 25 V electrical pulse load, when it is switched from original stable position, i.e., the transmission state, to the second bi-stable position, i.e., the switching state. Additionally the switching time of backward moving only costs 1 ms under the same driving condition. The background behind the difference between 5 and 1 ms can be simply explained as that the energy barrier, i.e., the critical strain energy, regarding to the backward moving of buckle spring is much less than the energy required for forward moving [9,16,17]. It also means that the critical strain energy regarding to spring deformation of backward moving of buckle spring is smaller than the one with respect to forward moving. Under the same and constant input electrical power to H-beam actuator, the generated static displacement of H-beam is time-dependent result. In the backward moving action, the H-beam actuator only needs time less than 1 ms to produce enough displacement to push the switch body and buckle springs to move to the position where the corresponding strain energy of buckle spring is over its critical energy barrier. Thereafter, the buckle springs will drive switch body to move further till buckle springs reach the initial stable position, i.e., the energy-wise stable position regarding to spring beam shape. In contrast to forward moving switching case, i.e., a time period which is slightly less than 5 ms, H-beam actuator requires longer time to generate larger displacement to move switch body and buckle springs from their initial rest position to second stable position. The longer actuation time means larger displacement and higher strain energy, because the critical strain energy of forward movement of buckle spring is higher than the one of backward moving. Besides, the other measured typical optical characteristics include that back reflection loss of −52 dB, cross-talk of −60 dB, insertion loss of 0.8 dB, polarization-dependent loss of 0.03 dB, and wavelength-dependent loss of 0.11 dB.

4. Conclusions

Combining a new H-beam actuator, movement link structure, reflective micro-mirror, and arched buckle spring to demonstrate a new compact latched 2×2 optical switch device is first reported and characterized in this article. This novel H-beam actuator provides bi-directional static displacement and bi-directional motion. This H-beam actuator is well functioned and exhibits good characteristics. This H-beam actuator can avoid the influence from rotational torques during its bi-directional dynamic and static movement due to its symmetric structural design. This 2×2 optical switch device driven by H-beam actuator can be operated with less than 5 ms switching time and under a 25 V dc electrical load.

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Biographies

Wen-Chih Chen received MS degree from National Tsing Hua University (Taiwan) in 2000. After that, he worked as an R&D engineer at Asia Pacific Microsystems Inc. and was responsible for developing optical MEMS components. He is currently working on his PhD in Power Mechanical Engineering Department at the National Tsing Hua University. His research interests are mainly in MEMS actuators and optical MEMS systems.

Chengkuo Lee received a MS degree in materials science and engineering from National Tsing Hua University, Hsinchu, Taiwan, in 1991. He also received a MS degree in industrial and system engineering from Rutgers University, New Brunswick, NJ, USA, in 1993. He received the PhD degree in precision engineering from the University of Tokyo, Tokyo, Japan, in January 1996. He worked as foreign researcher in Research Center for Advanced Science and Technology (RCAST) of the University of Tokyo in 1996. He had also worked in Mechanical Engineering Laboratory, AIST, MITI of Japan, as a research fellow in 1996. Thereafter, he was a senior research staff of Microsystems Laboratory, Industrial Technology Research Institute, Hsinchu, Taiwan. Since September 1997, he has joined the Metrodyne Microsystem Corporation, Hsinchu, Taiwan, and established the MEMS device division and micro-machining fab. He was the manager of MEMS device division between 1997 and 2000. He had been the adjunct assistant professor in Electro-Physics Department of National Chiao Tung University in 1998, and the adjunct assistant professor in Institute of Precision Engineering of National Chung Hsing University since 2001. He co-founded the Asia Pacific Microsystems, Inc., Hsinchu, Taiwan, in August 2001. Currently, he is the Vice President of Asia Pacific Microsystems, Inc. He has contributed more than 100 international conference papers and international journal articles in MEMS field. He is the member of IEEE, MRS, and IEE Japan. He received the IUMRS Graduate Student Award in 1994.

Chia-Yu Wu received his BE and ME degrees in power mechanical engineering from National Tsing Hua University, Hsinchu, Taiwan in 2000 and 2002, respectively. He joined Asia Pacific Microsystems, Inc., Hsinchu, Taiwan, in 2002 and is now a RF design engineer.

Weileun Fang was born in Taipei, Taiwan, in 1962. He received his PhD degree from Carnegie Mellon University in 1995. His doctoral research focused on the determining of the mechanical properties of thin films using micromachined structures. In 1995, he worked as a postdoctoral research at Synchrotron Radiation Research Center, Taiwan. He joined the Power Mechanical Engineering Department at the National Tsing Hua University (Taiwan) in 1996, where he is now a Professor as well as Faculty of MEMS Institute. From June to September 1999, he was with Prof. Y.-C. Tai at California Inst. Tech. as a visiting associate. He has established a MEMS testing and characterization lab. His research interests include MEMS with emphasis on micro fabrication/packaging technologies, micro optical systems, microactuators, and the characterization of the mechanical properties of thin films.