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Sensors and Actuators A 103 (2003) 109–115

SENSORS AND ACTUATORS A PHYSICAL

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An integrated micro-optical system for VCSEL-to-fiber active alignment[☆]

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Abstract

In this paper, a new micro-optical system for VCSEL-to-fiber active alignment is described. An integrated microsystem platform, which has a thermally-actuated micromirror, a silicon etched v-groove and flip-chip function, is successfully fabricated and actuated for beam adjustment from a vertical-cavity surface-emitting laser (VCSEL) to a fiber. The micro-optical system has 4.0° maximum beam steering angle with the resolution of 0.08°/mA. With the steering angle reaching 2.5°, the coupling efficiency from the VCSEL to the fiber improves to more than 80% from 9% initial efficiency of 25 μm misaligned fiber position.

Keywords: MEMS; Micromirror; VCSEL; Optical fiber; Coupling efficiency; Alignment

1. Introduction

A laser-to-fiber coupling module is one of the most important and key elements in optical fiber networks. Its main function is adjusting and coupling the beam generated from a semiconductor laser to optical fibers. Currently, laser-to-fiber couplings are predominantly used to transmit data signals in optical communications. Although existing commercial laser-to-fiber couplings have high coupling efficiency, they commonly need time-consuming fabrication processes and expensive external robotic control for adjusting laser-to-fiber optical alignment. In spite of a great demand of laser-to-fiber couplings, under the present condition the supply does not meet the demand in the optoelectronics packaging industry. Therefore, different alignment concepts have been recently proposed and used as inexpensive optoelectronics packaging technologies. They generally use etched v-grooves or the solder self-alignment function to align laser/fiber positions and achieve high coupling efficiency [1–3]. However, the accuracy of those passive alignment methods cannot be improved better than ±2 μm in high throughput manufacturing. It is difficult to say that this accuracy is sufficient enough for high performance and highly reliable optical communications. There are no well-established optical connection technologies good enough to apply for future optical communication and packaging.

Micro-electro-mechanical systems (MEMS) technology is an attractive way to direct and adjust a laser beam into an optical fiber, and assemble laser-to-fiber coupling modules due to its inherent advantages such as size, cost and sub-microscale tunability. One attempt at a laser-to-fiber coupling module using an MEMS micromirror has been demonstrated [4,5]. The 40% coupling efficiency was achieved from a laser to a single-mode fiber and the results showed that MEMS have high potential for application in a laser-to-fiber coupling system. However, their laser-to-fiber coupling concept will not be applicable for vertical-cavity surface-emitting laser (VCSEL) based modules that will be dominant in the future optical communications. The coupling system was designed based on traditional edge emitting lasers and fibers. Also since their packaging method is only on a laboratory level and still relies on external alignment of each component, it cannot be replaced with fully automated mass productive fabrication and packaging processes. Moreover, the components configuration and the large actuator mechanism negate the inherent size advantage of MEMS.

[☆] This paper was presented at the 15th IEEE MEMS conference, held in Las Vegas, USA, January 20–24, 2002, and is an expansion of the abstract as printed in the Technical Digest of this meeting.

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PII: S0924-4247(02)00313-8

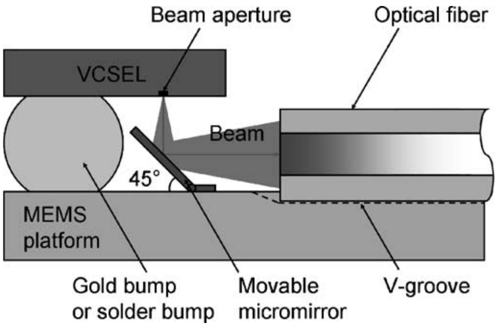


Fig. 1. A cross-sectional schematic view of VCSEL-to-fiber coupling concept.

We have designed and fabricated a new integrated micro-optical system for laser-to-fiber coupling alignment. Fig. 1 shows a cross-sectional schematic of our laser-to-fiber active alignment concept. The compact module consists of three parts: a VCSEL, an MEMS platform that has a thermally-actuated micromirror, and an optical fiber. The VCSEL is flip-chipped on the MEMS platform and is placed above the micromirror. The optical fiber is mounted on a v-groove etched in the MEMS platform to achieve ±2 μm passive alignment accuracy. The laser beam from the VCSEL is reflected and steered by the actuated micromirror to couple to the fiber. The optical coupling tuning between the VCSEL and the fiber can be actively achieved without external alignment controls.

The device is designed and packaged with mass production in mind, all of the processes used in the fabrication of this laser-to-fiber coupling are compatible with existing MEMS and optoelectronics packaging manufacturing technologies such as flip-chip bonding, anisotropic silicon bulk etching, solder self-assembly and micro-mechanical locking systems [6]. Therefore, the device fabrication processes can be fully automated by using existing manufacturing infrastructure. Since all functions are monolithically integrated in the MEMS platform, there is no need to use extra dies or components. Thus this well-organized micro-optical system can be inserted into existing commercial VCSEL-to-fiber or VCSEL-to-waveguide modules that are based on the optical packaging technique of light emitting from a VCSEL and coupled to a fiber/waveguide through a fixed 45° reflector [7,8]. In this paper the details of the design, fabrication process and testing of the micro-optical system for active alignment are described.

2. Design and fabrication

The MEMS platform is designed and fabricated using the multi-user MEMS processes (MUMPs) foundry at JDS Uniphase [9]. The MUMPs process provides two structural polysilicon layers, two phosphosilicate glass (PSG) sacrificial layers and a metal layer. Fig. 2 shows the pre-assembled MEMS platform before removing sacrificial layers. Also Fig. 3 shows a close-up view of the movable micromirror after solder self-assembly. Before removal of the PSG sacrificial layers, a v-groove is anisotropically etched to a 15 μm depth using an EDP (ethylenediamine pyrocatechol) solution. Then the solder connections are preformed between two solder pads, one on the MEMS micromirror supporting frames and the other one on the base of the MEMS platform using 0.004-mil diameter Sn63Pb37 eutectic solder balls. The stacked gold bumps are fabricated using a wire bonding machine and used as a connection post to flip-chip the VCSEL die. The movable micromirror structure consists of two stacked polysilicon (poly-1 and poly-2)

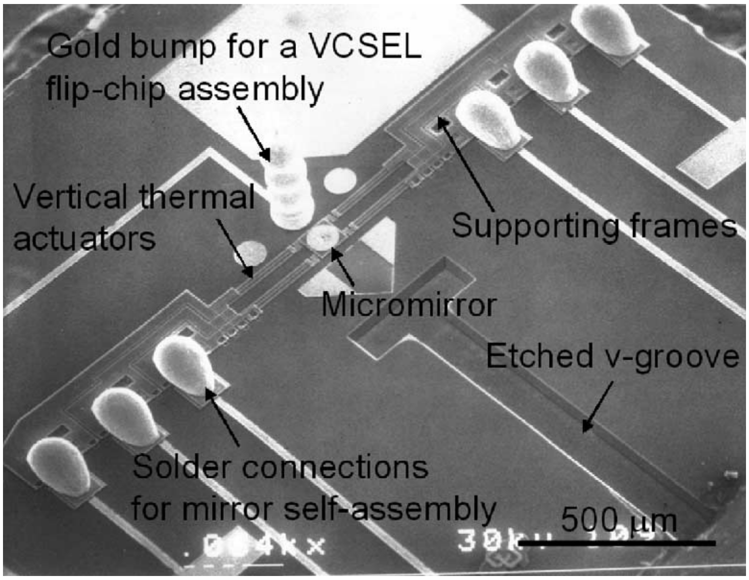


Fig. 2. A top-view micrograph of the pre-assembled MEMS platform.

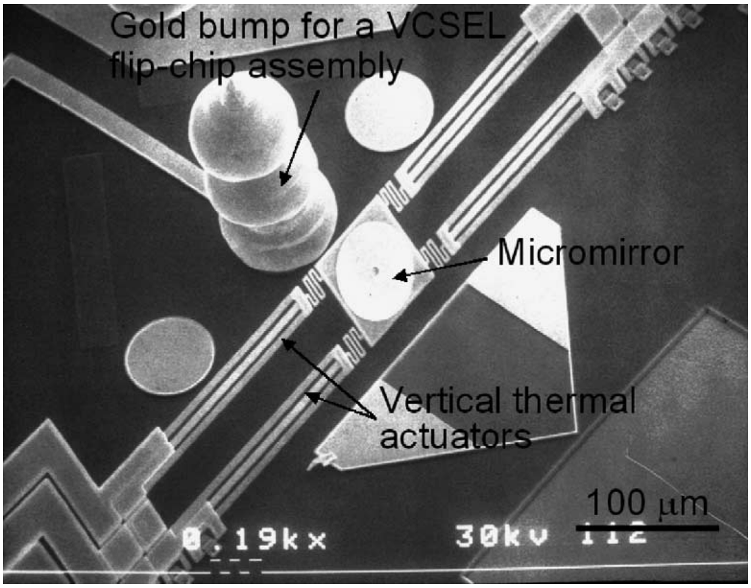


Fig. 3. A close-up view of the micromirror assembled to 45° relative to the substrate.

layers with a metal layer. The square mirror plate has an area of 80 μm × 80 μm with a 72 μm diameter metal layer. The micromirror is suspended by four vertical thermal actuators, and the actuators are connected to the supporting frames [10]. These structures are lifted up using a solder self-assembly process, which fixes them at 45° with mechanical locking mechanisms. Electrical power for actuators comes from the substrate through the solder connections.

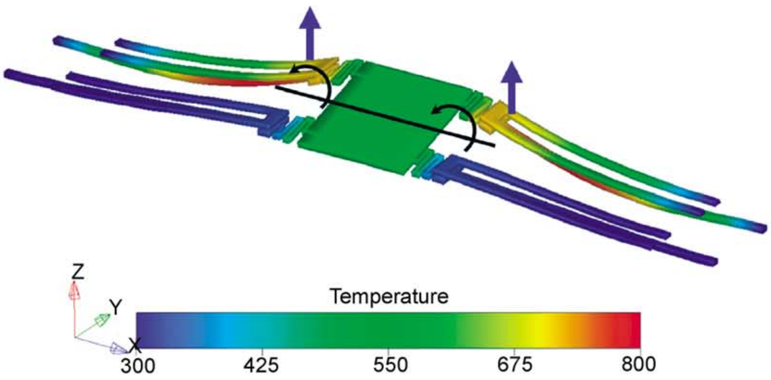
As shown in Fig. 1, the butt-coupling concept is used to demonstrate the VCSEL-to-fiber coupling. Therefore, the 45° micromirror only needs two degrees of freedom to steer the beam from the VCSEL into the fiber. The combination of the motions of four vertical thermal actuators provides the two-dimensional mirror motions. Applying current, arms of a vertical actuator are heated up due to high resistivity. Because of the difference of dimension and thermal expansion difference between a center poly-1 cantilever with 200 μm length (hot arm) and side poly-2 cantilevers with 160 μm length (cold arms), a single vertical thermal actuator shows up-and-down motion. By controlling each actuator, the micromirror can be two-dimensionally steered. When driving only two upper actuators, the micromirror rotates vertically as shown in Fig. 4(a). Using the same principle, the micromirror is steered laterally by driving the two right side actuators as shown in Fig. 4(b). The maximum beam steering angle of 4.0° can be, respectively, achieved in both vertical and lateral directions. Also when only one actuator is moved, the micromirror can be tilted diagonally as shown in Fig. 4(c). The combination of thermal actuator motions provides a 15 μm radius steerable area at the tip of the optical fiber placed at a 300 μm distance from the micromirror.

This mirror controllability is large enough to adjust the beam. The v-groove provides ±2 μm coarse fiber position alignment but ±8 μm misalignment is generated during assemblies such as the VCSEL die flip-chip and the micromirror solder self-assembly. Therefore, total ±10 μm misalignment is possible to generate after all assemblies. However, since the movable micromirror has 15 μm radius shooting area, all misalignments can be compensated. Fig. 5 shows the relationship between two actuators driving current and the beam steering angle. The micromirror displays fine controllability with an actuation rate of 0.08°/mA. Thus precise tunability provides sub-micron adjustment at the tip of the optical fiber in the micro-optical system.

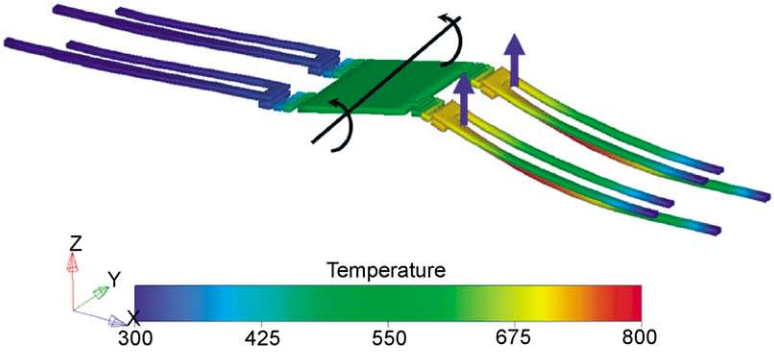
Fig. 6 shows the completely assembled 2 mm × 2 mm MEMS platform with the flip-chipped VCSEL. After lifting up the mirror structure, the VCSEL laser chip (size: 500 μm × 500 μm × 250 μm (thickness)) is flip-chipped facedown above the micromirror, and the backside ground electrode of the VCSEL is connected with the substrate using conductive epoxy. The final gap between the VCSEL and the MEMS platform after the flip-chip process is 65 μm. Last of all, the optical fiber is mounted and glued onto the v-groove. The final device size is quite compact, and it is reasonable to say that the packaging approach has scalability to VCSEL-to-fiber coupling arrays. Fig. 7 shows the final packaged VCSEL-to-fiber alignment module. Because of its compactness and well integration, the micro-optical system can be easily packaged using standard optoelectronics packages.

To fabricate the aligned VCSEL-to-fiber coupling prototype, an existing VCSEL chip is used. Therefore, the design flexibility of the MEMS platform structure is restricted by the VCSEL configuration such as the chip size, the electrode position and the beam aperture position. However, our laser-to-fiber coupling concept will be more manufacturable if a

(a) vertical tilting



(b) lateral tilting



(c) diagonal tilting

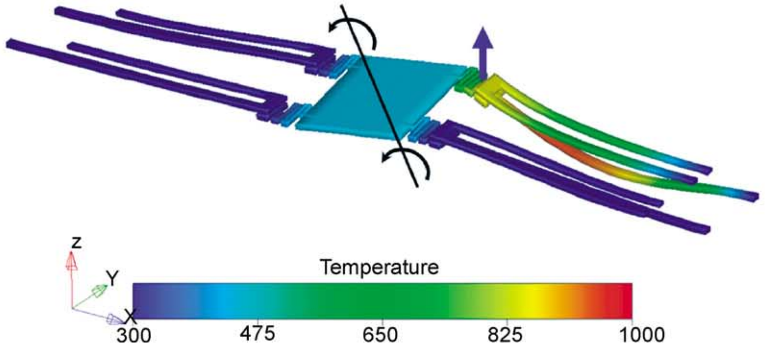


Fig. 4. Schematic representation of two-dimensional mirror motions: (a) vertical tilting; (b) lateral tilting; (c) diagonal tilting.

suitable VCSEL chip is used. For example, if all electrodes are larger and on the one side, the VCSEL bonding process becomes much simpler and the design flexibility of micromirror is also expanded. Also a gold bump was used as a flip-chip connection post of the VCSEL because of the VCSEL design limitation. However, if the VCSEL has enough room to put solder, the VCSEL flip-chip process can be done with other solder reflow processes at the same time, and the total fabrication processes become much simpler. It results in reducing time and cost.

3. Results

The coupling efficiency from the VCSEL to the multi-mode fiber is measured. The coupling efficiency is defined as the ratio between the VCSEL output power and the optical intensity obtained from the fiber end through the micro-optical system. Testing module is shown in Figs. 6 and 7. Optical intensity is measured by using an optical power meter. The VCSEL output power is 375 μW with an 850 nm wavelength, and a 100 μm core-diameter multi-mode fiber is

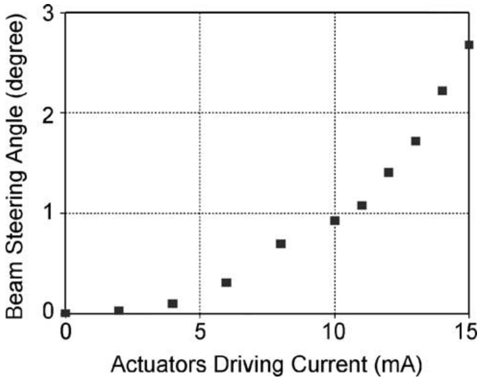


Fig. 5. Beam steering angle as a function of actuators driving current.

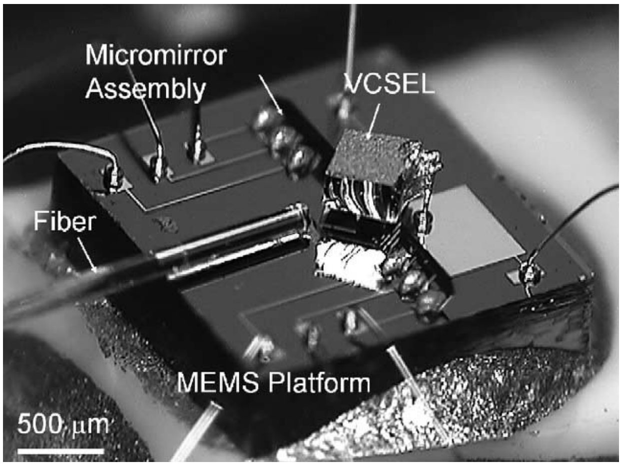


Fig. 6. A photograph of the completed micro-optical system for laser-to-fiber coupling.

used as a fiber coupling. The total optical path length from the VCSEL to the fiber end is 500 μm.

Fig. 8 shows the coupling efficiency as a function of the beam steering angle when the optical fiber is optimally mounted on the v-groove. Moving two side actuators and laterally steering from left to right, the VCSEL-to-multi-mode fiber coupling efficiency can be changed and a maximum coupling efficiency of 80% is achieved. This graph shows that the micro-optical system is quite powerful to control the VCSEL beam direction. Fig. 9(a) and (b) shows the ability of the micromirror to compensate for an optical fiber that is laterally offset 25 and 50 μm from the center of the v-groove.

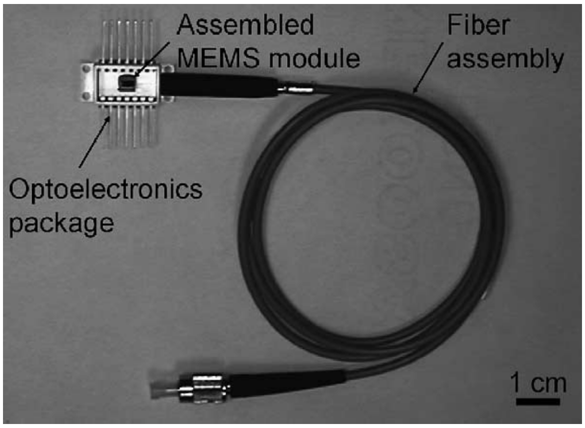


Fig. 7. A final packaged VCSEL-to-fiber alignment module.

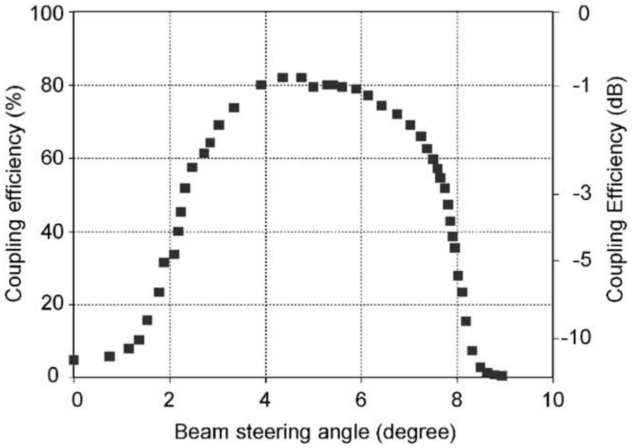


Fig. 8. Coupling efficiency as a function of beam steering angle (lateral mirror tilt).

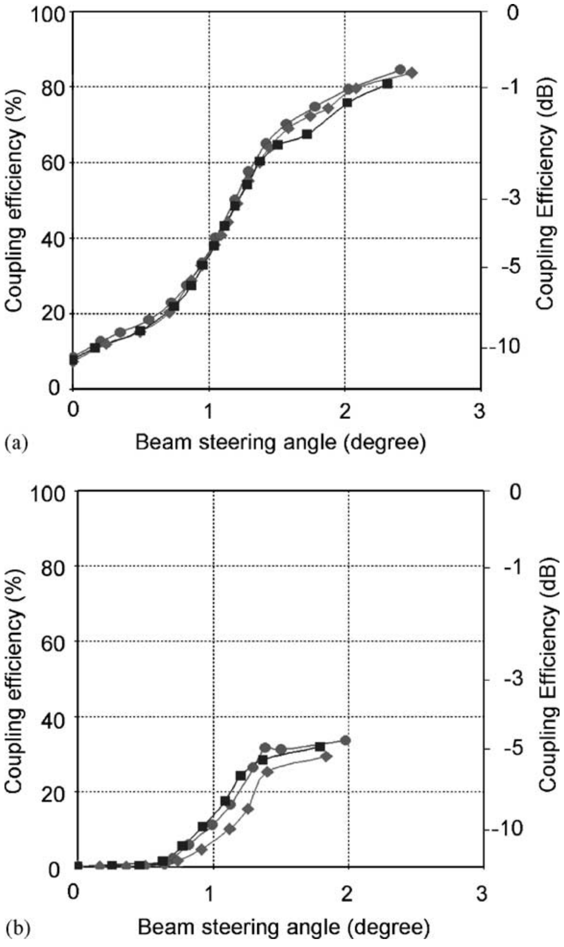


Fig. 9. Coupling efficiency change versus the beam steering angle for a fiber shifted laterally: (a) 25 μm; (b) 50 μm.

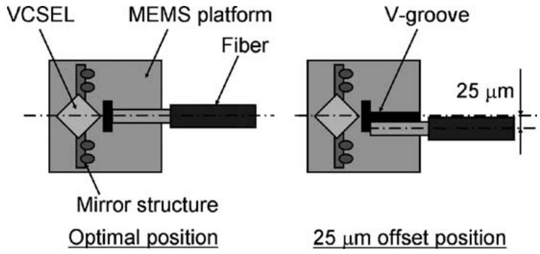


Fig. 10. A schematic illustration of the coupling efficiency measurement set-up (25 μm offset case).

A schematic illustration of this experimental arrangement is shown in Fig. 10. For instance, in Fig. 9(a), although the initial coupling efficiency is 9%, the coupling efficiency is significantly improved according by the change in beam steering angle, and a maximum coupling efficiency of more than 80% is obtained. The result shows that the micromirror can compensate a fiber position misalignment within 25 μm. As shown in Fig. 9(b), even if there is 50 μm offset, the micro-optical system can compensate the misalignment and enhance the coupling efficiency. Fig. 11(a) and (b) show the results of vertical adjustment with 25 and 50 μm offset. The coupling efficiencies in both cases are improved as well.

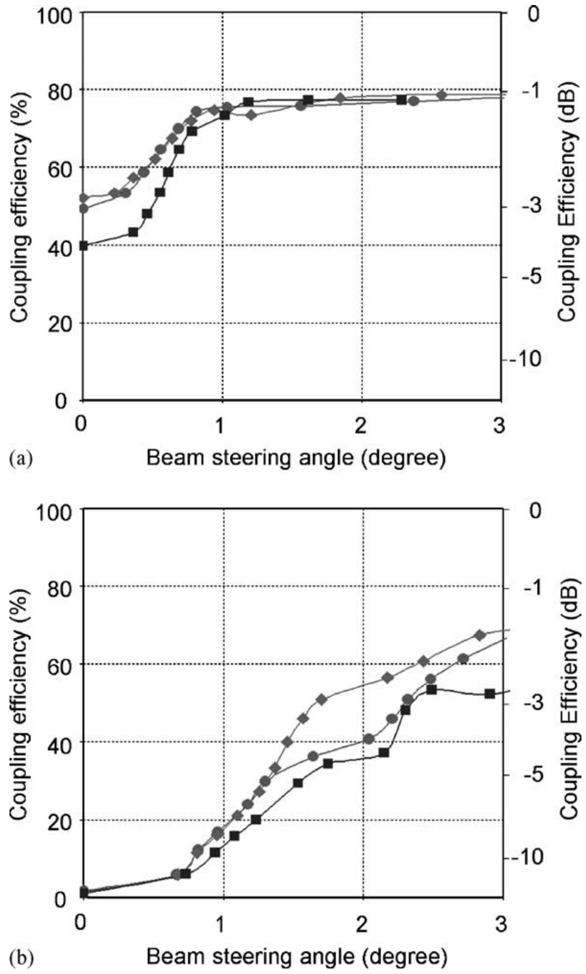


Fig. 11. Coupling efficiency change versus the beam steering angle for a fiber shifted vertically: (a) 25 μm; (b) 50 μm.

In the integrated micro-optical system, total positioning misalignment during fabrication is predicted as ±10 μm as mentioned before. Thus, the results of the beam steering performance tests show that the MEMS platform does not need external alignment or manipulation to assemble lasers and fibers. Therefore, the fabrication processes can be fully automated and mass productive. Also good alignment repeatability appears in measured results. We obtained the same hysteresis in three separate measurements.

4. Conclusion

A new micro-optical system for VCSEL-to-fiber active alignment is successfully demonstrated using MEMS and optoelectronics packaging technologies. The prototype shows not only packagability but also high performance in coupling a beam to couple to an optical fiber. It is concluded that the simple alignment concept can be applied to current coupling modules without extra cost, and enhances coupling efficiency from a laser to a fiber.

The primary advantages of the new MEMS-based VCSEL-to-fiber coupling approach are:

(1) Fully automated active alignment can be provided without using external expensive precision robotic control.
(2) Batch assembly with hundreds of MEMS-actuated VCSEL-to-fiber alignments is possible due to mass productive module configuration.
(3) The module assembling processes are compatible with existing passive and high-speed placement of the VCSEL and the fiber onto the platform.
(4) The compact, simple module concept has scalability for VCSEL-to-fiber arrays.

However, in laser-to-fiber coupling products, the micromirror position has to be permanently fixed. In this paper, the prototype does not include structures to fix the mirror position, and a method of holding the position has not been reported. In future, the details of the fixing mechanism for a second generation device will be reported.

Acknowledgements

This research and development was partially funded by DARPA: FAME grant no. F33615-98-C-5429. The authors would like to thank Christine Mollenkopf of Cielo Communications, Wenge Zhang, Kevin Harsh and Brian Schaible for their valuable discussions during this research. The authors also wish to thank NHK Spring Co., Ltd. for their support.

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Adisorn Tuantranont received his BS degree in electrical engineering from King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand, in 1995 and MS and PhD degrees in electrical engineering from University of Colorado at Boulder, in 1998 and 2001, respectively. He is currently working on MEMS and optical communication systems.

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Yung-Cheng Lee received his BSME degree from the National Taiwan University in 1978, and the MS and PhD degrees from the University of Minnesota, in 1982 and 1984, respectively. He is a Professor of Mechanical Engineering, Acting Director of NSF Center for Advanced Manufacturing and Packaging of Microwave, Optical and Digital Electronics, University of Colorado at Boulder. Prior to joining the university, he was a member of Technical Staff at AT&T Bell Laboratories, Murray Hill, NJ. His research activities include low-cost prototyping and thermal management of multichip modules, 3D packaging, self-aligning soldering, fluxless or solderless flip-chip connections, optoelectronics packaging, process control using fuzzy-logic models and MEMS design and packaging. He is an Associate Editor of ASME Journal of Electronic Packaging.