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Micromachined free-space integrated micro-optics

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Abstract

The surface-micromachining technique has been employed to fabricate novel three-dimensional micro-optical elements for free-space integrated optics. The optical axes of these optical elements are parallel to the substrate, which enables the entire free-space optical system to be integrated on a single substrate. Microscale Fresnel lenses, mirrors, beam-splitters, gratings, and precision optical mounts have been successfully fabricated and characterized. In addition, micropositioners such as rotary stages and linear translational stages are monolithically integrated with the optical components using the same surface-micromachining process to provide on-chip optical alignment or optomechanical switching. Self-aligned hybrid integration with semiconductor edge-emitting lasers and vertical cavity surface-emitting lasers are also demonstrated for the first time. This new free-space micro-optical bench (FSMOB) technology could significantly reduce the size, weight, and cost of most optical systems, and could have a significant impact on optical switching, optical sensing and optical data-storage systems as well as on the packaging of optoelectronic components.

Keywords: Free-space integrated optics; Micro-optical elements

1. Introduction

Free-space integrated optics in which photons propagate in free space between optical elements has many applications in optical interconnection, sensing, display, and optical data-storage systems. Micromachining allows inexpensive and reproducible batch processing of micro-optical components [1,2]. It also enables wafer-scale integration of micro-optical systems. In addition to passive optical elements, micro-actuators and micromechanical stages can also be monolithically incorporated into the optical systems. Many micromachined free-space optical components have been demonstrated, including scanning mirrors [3], digital micromirrors [4], and a deformable grating light valve [5] for display applications, microfabricated optical choppers [6], and micromotor gratings [7]. However, most of these components are designed to have surface-normal optical access because the optical elements are confined to the plane of the substrate. Therefore, it is not possible to cascade two or more optical elements along the optical axes without the help of external optical elements. As a result, they are not suitable for integrating the entire optical system on a chip.

Integrating the entire optical system on a single substrate has many advantages. The optics can be pre-aligned in the design and layout stage for these micro-optical systems. Most of the expensive assembly and packaging processes for individual optical components can be eliminated. The system cost, size, and weight are significantly reduced. One of the main challenges for implementing such free-space micro-optical systems monolithically is the lack of microfabricated out-of-plane optical elements whose optical axes are parallel to the substrate. Since the optical beams are usually expanded in free-space optics, optical elements with diameters and heights larger than a few hundred micrometers are needed. Such tall three-dimensional micro-optical elements are difficult to fabricate using conventional microfabrication techniques.

Previously, using a surface-micromachined microhinge technology [8], an out-of-plane, three-dimensional micro-Fresnel lens has been demonstrated [9]. Similar techniques have been applied to fabricate out-of-plane microgratings, micromirrors [10], etalons [11], and other elements. More significantly, these micro-optical elements can be integrated with various types of micropositioners, such as rotary stages or linear translation stages, using the same surface-micromachining techniques [10]. A sliding–tilting micromirror for coupling lasers to optical fibers [12], a three-dimensional corner cube reflector with torsion modulators [13], and a 2×2 free-space fiber-optic switch [14] have also been demonstrated. The microhinge technology allows the out-of-plane optical elements to be batch fabricated using conventional planar processes and then folded into three-dimensional structures. These structures can also be utilized to position precisely the active optoelectronic components that cannot be fabricated monolithically [15,16]. In this paper, we present the design, fabrication processes, and measurement results of various integrable three-dimensional micro-optical elements an integrated micropositioners. Their applications in free-space integrated micro-optic systems will also be discussed.

2. Design and fabrication

The concept of our free-space integrated micro-optical system is illustrated in Fig. 1. Passive optical components such as lenses, mirrors, beam splitters, and gratings are made by the surface-micromachined microhinge technology. They can be integrated with various types of micropositioners (microscale rotary stages or linear translational stages) and microactuators [17] for precise optical alignment or optomechanical switching. Some active optoelectronic devices such as photodetectors can be built monolithically on the Si substrate, while semiconductor laser or light-emitting diode (LED) sources can be incorporated by hybrid integration with passive optical alignment. Additional electronic signal-processing and control circuits can be added for closed-loop control of the micropositioners. The substrate serves as a free-space micro-optical bench (FSMOB) for the integrated optics.

The schematic diagram of a three-dimensional micro-Fresnel lens before it is fully assembled is shown in Fig. 2. It consists of two structural polysilicon layers with interlaced sacrificial layers. The fabrication processes are described in the following: first, a 2 μm thick phosphosilicate glass (PSG-1) layer is deposited on the silicon substrate as the sacrificial material. It is followed by the deposition of a 2 μm thick polysilicon layer (poly-1) on which the micro-optics patterns such as Fresnel lenses, mirrors, beam splitters, and gratings are defined by photolithography and chlorine-based dry etching. The hinge pins holding these three-dimensional structures are also defined on this layer. Following the deposition and patterning of poly-1, another layer of sacrificial material (PSG-2) of 0.5 μm thickness is deposited. The supporting structures such as staples and spring latches are defined on the second polysilicon (poly-2) layer. The bases of the staples and torsion springs are fixed on the Si substrate by opening contact holes through both PSG-2 and PSG-1 before the deposition of the poly-2 layer. The poly-2 structures can also be contacted with poly-1 by etching contact holes through PSG-2 only, as required in the rotatable mirrors and gratings that will be described later. The micro-optics plates are released from the substrate by selectively removing the PSG material using hydrofluoric acid after fabrication. After the release etching, the polysilicon plates with micro-optic patterns are free to rotate out of the substrate plane. The angles between the plates and the substrate are coarsely defined by the length of the spring latches. Various types of coatings are applied to the three-dimensional optics plates. For example, a thick layer of gold is coated to improve the reflectivity of micromirrors, or to block light transmission through the dark zones of Fresnel zone plates. On the other hand, a thin layer of gold is used for partially transmitting mirrors or beam splitters. Dielectric coating could also be employed. The coating could be done either before or after assembly.

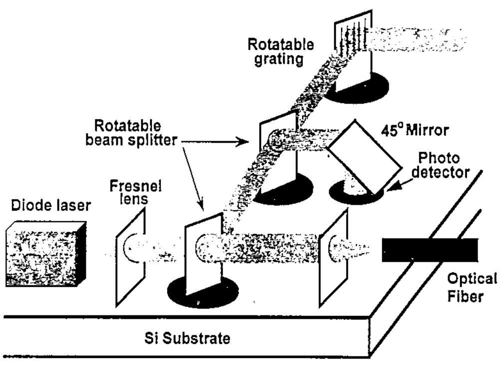

Fig. 1. Schematic diagram illustrating the concept of free-space micro-optical bench on a chip.

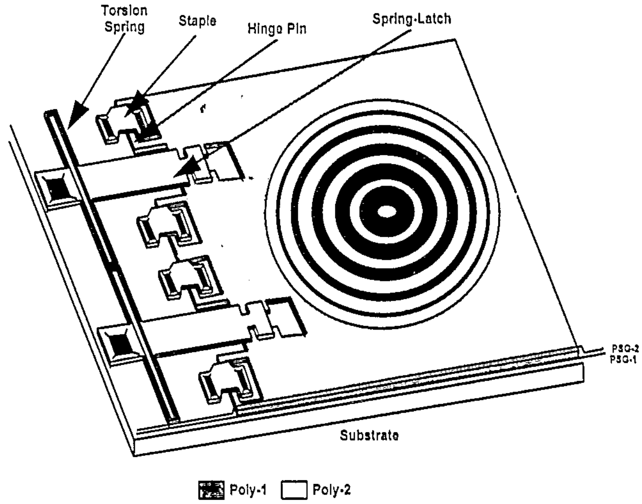

Fig. 2. Schematic diagram of the three-dimensional micro-Fresnel lens before assembly.

3. Results and discussion

3.1. Micro-Fresnel lenses

A three-dimensional micro-Fresnel lens has been fabricated and characterized. The Fresnel zone pattern is defined on the first polysilicon layer by photolithography and dry etching. The lens shown in Fig. 3 has a diameter of 650 μm and a primary focal length of 1 mm. The optical axis is 1 mm above the Si surface, and the height of the lens plate is 1.4 mm. Because of the height of the lens plate, the angles between the lens plates and the substrate have some variations even though they are coarsely fixed by the spring latches. Such variations are not tolerable in large optical systems. We

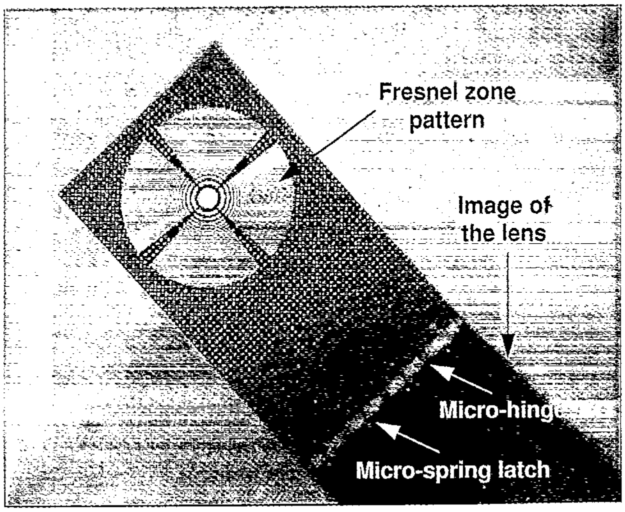

Fig. 3. Photograph of a 1.4 mm high three-dimensional micro-Fresnel lens. It has a diameter of 650 μm, focal length of 1 mm, and an optical axis 1 mm above the Si surface.

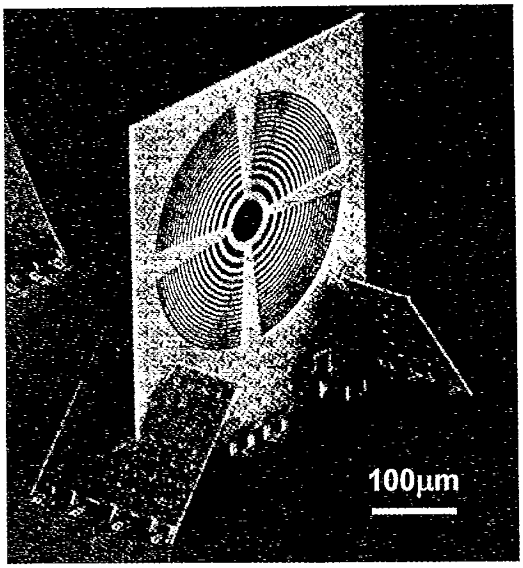

Fig. 4. SEM micrograph of a three-dimensional micro-Fresnel lens with precision lens mount.

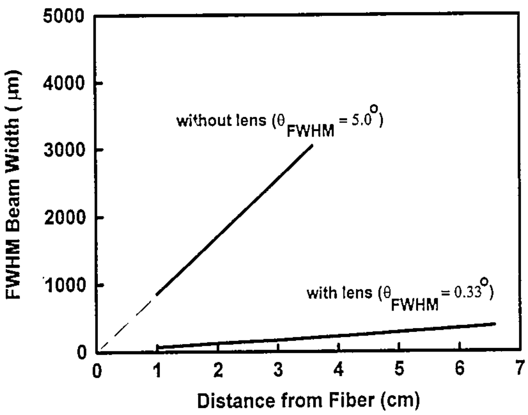

Fig. 5. Divergence angles of optical beams emitted from a single-mode optical fiber with and without the collimating micro-Fresnel lens.

have designed a new 'lens-mount' to define precisely the angles of the three-dimensional micro-optical elements. The lens-mount consists of two hinged polysilicon plates that are orthogonal to the lens plate. It has a V-shaped opening at the top to guide the lens plate into a 2 μm wide groove. A tilting angle smaller than 0.5° can be achieved. The scanning electron micrograph (SEM) of an assembled micro-Fresnel lens with precision lens mount is shown in Fig. 4. The diameter of this lens is 280 μm, and the optical axis is 254 μm above the silicon surface. A smaller tilting angle can be achieved by employing a lens mount with deeper grooves or with multiple mounting plates with different heights. The lens mounts also improve the mechanical strength and stability of the micro-optical elements.

To characterize its optical performance, the micro-Fresnel lens is used to collimate a divergent beam emitted from a single-mode fiber at $\lambda = 1.3$ μm. Fig. 5 compares the divergence angles of the optical beams with and without the collimating lens. The intensity full-width-at-half-maximum (FWHM) angle is reduced from 5.0 to 0.33°. The collimated beam profile fits very well to the Gaussian shape (95% fit). The diffraction efficiency of the micro-Fresnel lens was measured to be 8.6% using the method described by Rastani et al. [18]. This is in agreement with the theoretical limit of binary-amplitude Fresnel zone plates. Higher theoretical diffraction efficiency of 41% can be achieved by binary-phase Fresnel lens.

3.2. Rotatable grating and mirrors

The micro-optical elements fabricated by surface micromachining can be integrated with micropositioners and micro-actuators without additional processing steps. This allows the pre-aligned micro-optical systems to be fine-adjusted by the on-chip micro-actuators. Optomechanical switches can also be realized by, for example, integrating an out-of-plane mirror with an actuated translational stage [14]. A three-dimensional micrograting has been successfully integrated with a rotary stage, as shown in Fig. 6. The rotatable plate, similar to the micromotor structure [19], is fabricated on the first polysilicon layer, and the axis and hub are defined on the second polysilicon layer. The micrograting is fabricated by a similar process except that the grating pattern is defined on the second polysilicon layer and the bases of the spring latch and staples (poly-2) are now connected to the rotatable plate on poly-1. The grating plate on poly-2 is connected to the microhinges defined on poly-1 through via holes. The micrograting has been characterized by an on-chip semiconductor laser source with collimating lens (to be described in Section 3.3). Diffraction patterns are successfully observed as the micrograting is rotated from −35 to +35°. Details of the experimental results are reported elsewhere [20].

A pair of micromirrors which forms a Fabry–Pérot etalon has also been integrated with a rotary stage. Fig. 7 shows the SEM micrograph of this structure when only one micromirror

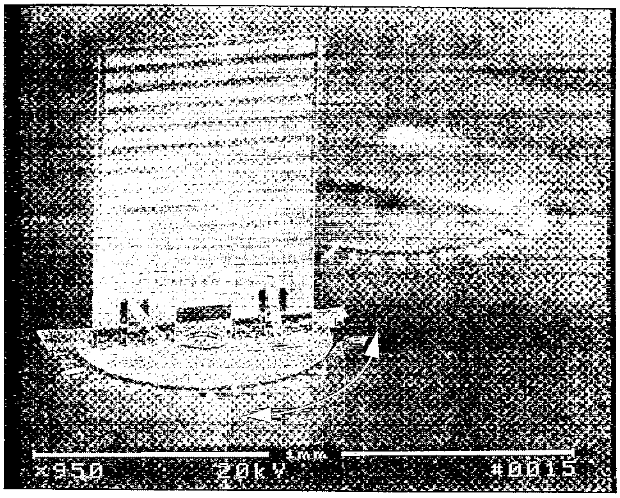

Fig. 6. SEM micrograph of a three-dimensional micrograting integrated with a rotary stage.

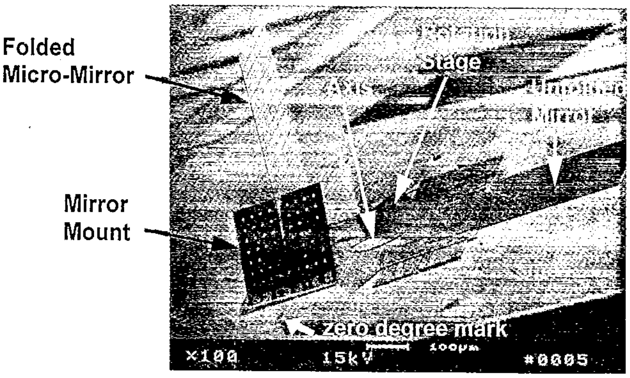

Fig. 7. SEM micrograph of a tunable Fabry–Pérot filter. One of the two micromirrors has been assembled. Wavelength tuning is achieved by rotating the filter, which has been rotated by 20° here.

is assembled. The dimensions of the mirror are 400 μm × 480 μm. As the stage is rotated, the transmission wavelength of the Fabry–Pérot etalon changes accordingly. Thus a tunable wavelength filter can be realized. The rotary stage in Fig. 7 has been rotated counter-clockwise by 20°, as shown by the angular scale (10° per tick) and zero-degree mark.

3.3. Three-dimensional self-alignment structures for semiconductor edge-emitting lasers

It is desirable to integrate monolithically as many passive and active micro-optical components as possible using surface-micromachining techniques so that minimum assembly and packaging are required. However, some optoelectronic components needed for optical systems (e.g., laser light sources) cannot be fabricated by this technique. To realize the entire free-space optical system on a single chip, new hybrid integration schemes with minimum optical alignment need to be developed. Hybrid optical packaging on silicon with flip-chip mounting and silica waveguide interconnection has been proposed [21]. However, the waveguide approach is not suitable for free-space integrated optics. In this section, novel three-dimensional self-alignment structures fabricated integrally with the micro-optical elements will be described.

Fig. 8(a) shows a schematic diagram illustrating the self-aligned hybrid integration scheme for a semiconductor edge-emitting laser and a micro-Fresnel lens [15]. In free-space optical systems, it is desirable to keep the optical axes of all optical elements at the same height. The active waveguide of the semiconductor laser should be aligned to the optical axis of the micromachined micro-optical elements (254 μm above the Si surface in our implementation). The edge-emitting laser is mounted on its side for accurate positioning of the active emitting spot. There are other possible schemes for mounting semiconductor lasers: upright mounting and flip-chip mounting. Since the substrate thickness of semiconductor lasers typically has a variation of ±5 μm, upright mounting is not suitable for a micro-optical bench unless additional adjustable optics is employed. Flip-chip mounting has better alignment accuracy (≈1 μm); however, the resulting emitting spot is too close to the Si surface and is much lower than the optical axis of the free-space optical system. Since the laser chip size can be precisely defined by scribing with an accuracy of around one micrometer, the emitting spot

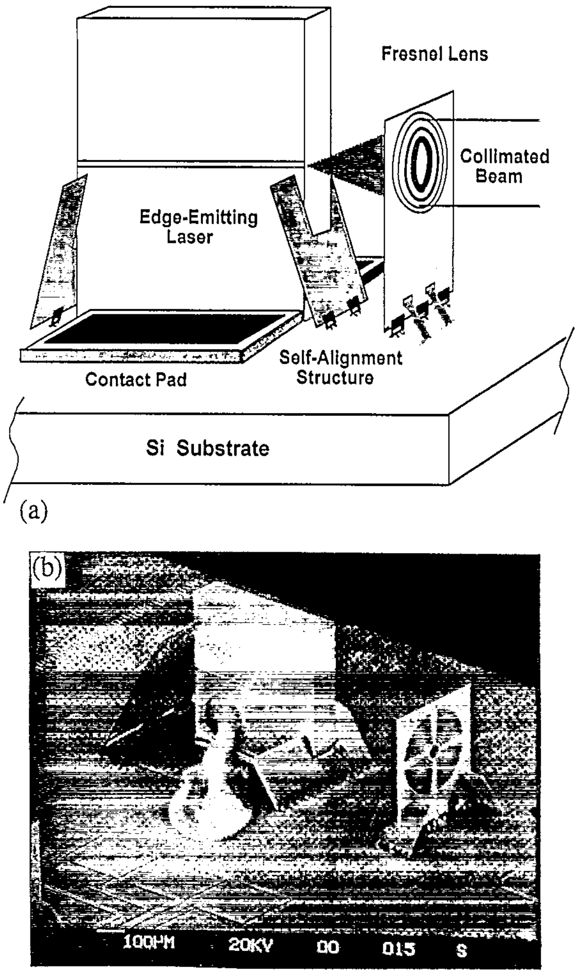

Fig. 8. (a) Schematic diagram and (b) SEM micrograph illustrating the self-aligned hybrid integration scheme of a semiconductor edge-emitting laser and a collimating micro-Fresnel lens.

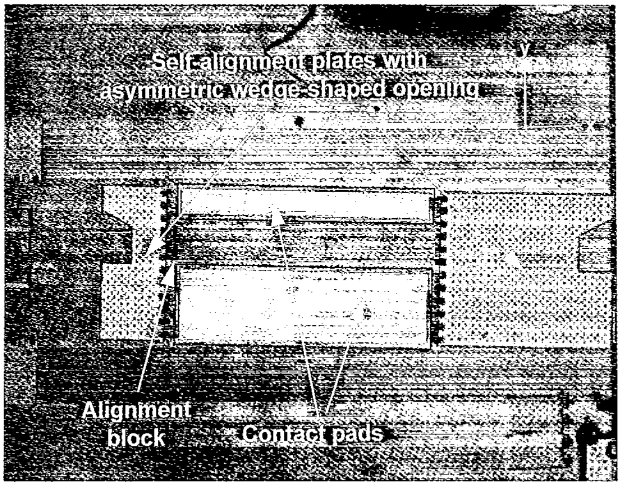

Fig. 9. Top view photograph of the self-aligned structure for semiconductor edge-emitting lasers before it is assembled.

can be aligned with the optical axis by side mounting. Submicrometer alignment accuracy in the out-of-plane direction could be accomplished by either on-chip vertical actuators [22] or a pair of 45° beam-steering mirrors to convert the vertical alignment into horizontal alignment [23].

Fig. 8(b) shows the SEM micrograph of the hybrid-integrated semiconductor edge-emitting laser/micro-Fresnel lens. The emitting spot of the laser is aligned to the center of the Fresnel lens by the self-alignment structures. Fig. 9 is the top-view photograph of the self-alignment structure before it is assembled. Two alignment plates are employed: one located at the front side of the laser and the other one at the back side. These alignment plates are pre-aligned with the lenses during the layout stage. The edge-emitting laser is slid into the slot between two electric contact pads until the front facet hits the alignment block build on the micro-optical bench, which defines the longitudinal position of the emitting spot. The self-alignment plates are then rotated out of the substrate plane to hold the laser chip. The asymmetric U-shaped opening on the plate gradually guides the active side (waveguide side) of the laser towards the flat edge of the openings, which are pre-aligned to the center of the micro-Fresnel lens. This unique design allows us to accommodate lasers with a large variation of substrate thickness (100–140 μm). Conductive silver epoxy is applied between the laser and the contact pads for the electrical contact in this initial demonstration. Potentially, the epoxy could be replaced by other three-dimensional micromechanical structures.

The optical performance of the integrated edge-emitting laser/micro-Fresnel lens set has been characterized. A diode laser with 1.3 μm wavelength is positioned at the focal point of a Fresnel lens with 500 μm focal length. The light emitted by the laser is collimated by the Fresnel lens. The collimated beam profile is shown in Fig. 10. The elliptical shape is due to the intrinsic asymmetric beam-profile characteristic of semiconductor edge-emitting lasers. The FWHM angles of the laser have been reduced from 18°×40° to 0.38°×0.9°. This compact integrated laser source has been used to illuminate an integrated three-dimensional rotatable micrograting [20].

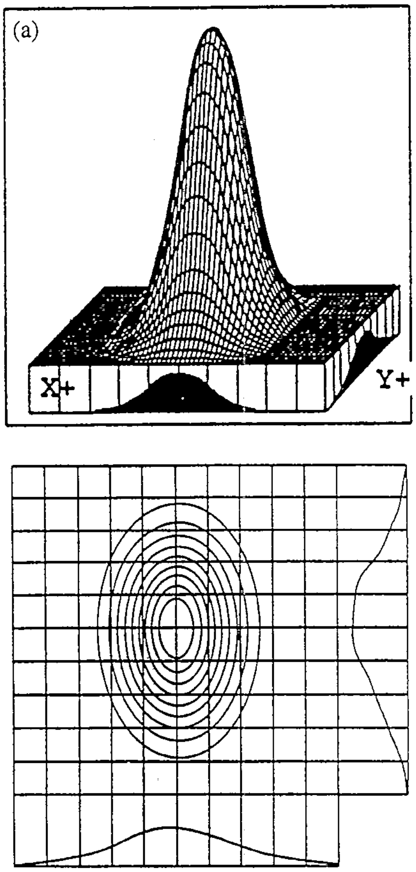

Fig. 10. (a) Three-dimensional profile and (b) contour plot of the optical beam from the integrated semiconductor edge-emitting laser/micro-Fresnel lens module. The elliptical shape is typical of edge-emitting lasers.

3.4. Arrays of vertical-cavity surface-emitting lasers and micro-Fresnel lenses

For optical interconnects and many other applications, vertical-cavity surface-emitting lasers (VCSELs) are desired because of their unique characteristics: low threshold current, circular far-field pattern, narrow beam divergence, and the ability to form two-dimensional arrays. The VCSEL is also particularly suitable for integrating with the microlenses using passive alignment because it has a small numerical aperture and, therefore, large misalignment tolerance. In addition, two-dimensional arrays can be formed in both VCSELs and microlenses. Therefore, the combination of the three-dimensional micro-Fresnel lens arrays with passively aligned VCSEL arrays is ideal for free-space optical interconnects (for example, between multichip modules) and laser array packaging. A self-aligned mounting scheme has been developed for integrating VCSELs with the micro-optical bench [16]. We have demonstrate the integration of 8×1 arrays of VCSELs and micro-Fresnel lenses using passive alignment.

A schematic diagram and the SEM micrograph of a vertical three-dimensional micro-Fresnel lens array and a VCSEL

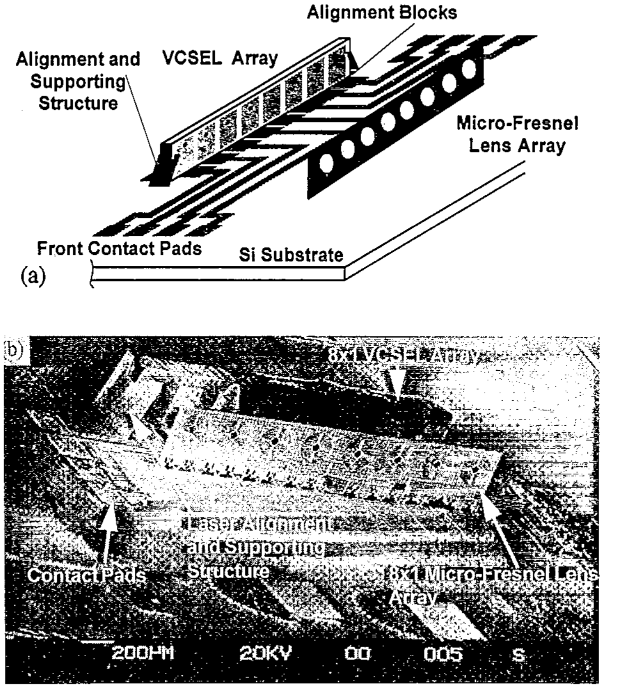

Fig. 11. (a) Schematic diagram and (b) SEM micrograph of the optical source array consisting of an 8 × 1 array of vertical-cavity surface-emitting lasers and an 8 × 1 array of micro-Fresnel lenses.

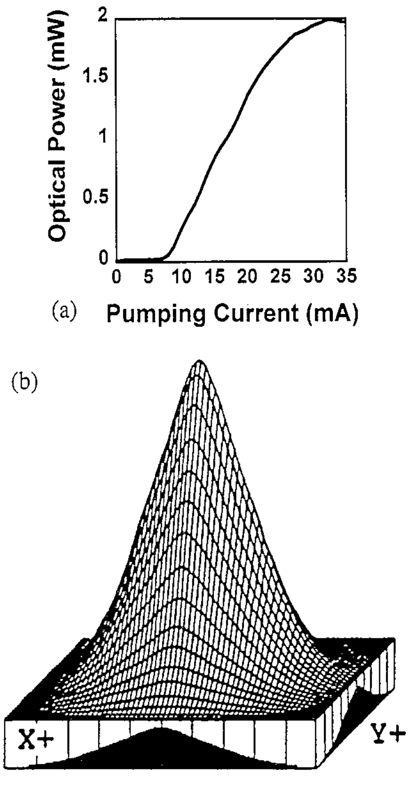

Fig. 12. (a) Light vs. current (*L–I*) characteristic and (b) optical beam profile of the output light from the integrated VCSEL/lens module.

array are shown in Fig. 11(a) and (b), respectively. The VCSELs fabricated at UCLA consist of an InGaAs/GaAs quantum-well active region sandwiched between two AlGaAs/GaAs quarter-wave distributed Bragg reflectors (DBRs) [16]. The emission wavelength is 0.98 μm. The

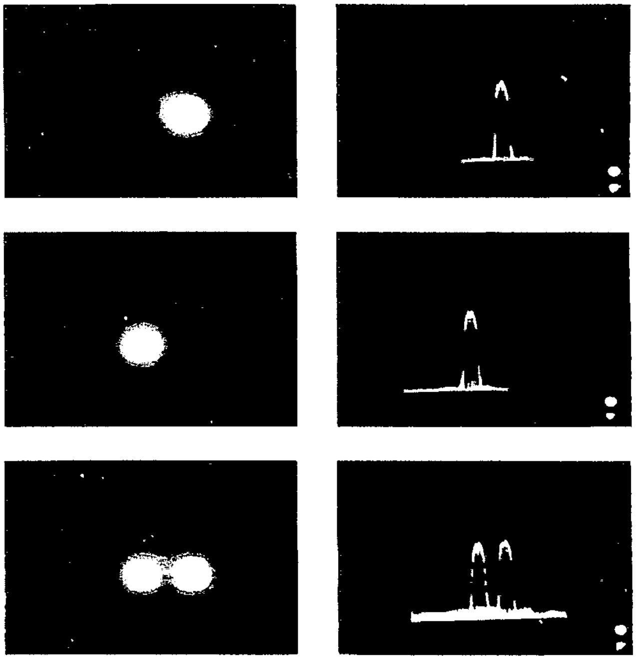

Fig. 13. Switching characteristics of the individually addressable VCSEL/lens array. The laser-to-laser spacing is 250 μm.

8 × 1 VCSEL array is 2 mm wide, 350 μm high, and 125 μm thick, and the spacing between individual VCSELs is 250 μm. The VCSEL array is also side-mounted so that the emitting spots match the optical axis of the lens array. Again, the tall three-dimensional alignment structures are built at the same time as the micro-Fresnel lens array. The alignment structures push the VCSEL array forward so that the front surface (emitting side) of the VCSEL array is aligned with the focal plane of the lens array. The optical power versus current characteristics and the output beam profile of the combined VCSEL/microlens module are shown in Fig. 12(a) and (b), respectively. The threshold current is the same as before mounting (4 mA for a 10 μm × 10 μm device). A very symmetric optical beam profile is observed. The VCSELs are individually addressable. The output beam patterns of two independently modulated VCSELs after passing through the integrated lenses are shown in Fig. 13.

4. Conclusions

In summary, a new surface-micromachined free-space micro-optical bench (FSMOB) for free-space integrated optics is proposed and successfully demonstrated. Various three-dimensional (out-of-plane) optical elements and micropositioners have been fabricated: micro-Fresnel lenses with various focal lengths, micromirrors, diffraction gratings, beam splitters, lens mounts, and linear and rotary stages. Integration of optical elements and micropositioners (e.g., gratings on a rotational stage) has also been demonstrated. Self-aligned hybrid integration of active optical devices with a FSMOB is realized by using novel three-dimensional alignment structures that can accommodate devices with various substrate thicknesses. This new approach can significantly reduce the size, weight, and cost of most optical systems, and has applications in free-space optical interconnects, optical sensors, switches, optical storage systems, and optoelectronic packaging.

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