Passively Aligned Hybrid Integration of 8 × 1 Micromachined Micro-Fresnel Lens Arrays and 8 × 1 Vertical-Cavity Surface-Emitting Laser Arrays for Free-Space Optical Interconnect

S. S. Lee, L. Y. Lin, K. S. J. Pister, *Member, IEEE,* M. C. Wu, *Member, IEEE,* H. C. Lee, and P. Grodzinski

Abstract— **Surface micromachining technique has been successfully applied to the fabrications of a three-dimensional 8 × 1 micro-Fresnel lens array and other novel three-dimensional alignment structures. With the help of these three-dimensional structures, self-aligned integration of the micro-Fresnel lens array and an 8 × 1 vertical-cavity surface-emitting laser (VCSEL) array is realized for the first time with passive alignment. Individual addressing of the VCSEL/micro-lens element is also successfully demonstrated. With their three-dimensional and array structural characteristics, they are very attractive for free-space optical interconnect and other integrated micro-optical systems.**

I. Introduction

FREE-SPACE optical interconnect has received increasing attentions from research community because of its potential to provide very high density routing and interconnection and its capability to implement sophisticated three-dimensional interconnection schemes [1], [2]. Optical interconnections for massively parallel computers often require one or two-dimensional arrays of optical modules that can be cascaded and monolithically integrated. Several implementations of optical interconnect using array devices have been reported [3], [4]. However, the optical elements used in these approaches lie in the plane of the substrates and are not suitable for monolithic integration. Previously, we have introduced a micromachined *free-space* micro-optical bench technology [5], [6] which enables both fixed and movable optical elements to stand perpendicular to the substrate. With this technology, a large number of free-space optical elements can be monolithically integrated on a single substrate.

Vertical-cavity surface-emitting lasers (VCSEL's) are preferred optical sources for optical interconnect because of their capability to form two-dimensional arrays, in addition to other unique advantages such as low threshold currents, circular output beam profile, and small beam divergence angles. It is therefore of great interest to combine the VCSEL arrays with other integrable micro-optical elements. Integration of planar micro-lenses with VCSEL's has been realized by etching a Fresnel pattern on the back side of the transparent GaAs substrate [7]. However, that approach cannot be extended to integrate more than two planes of optical elements as required by most optical interconnect circuits. In this paper, we report on a novel *three-dimensional* micro-Fresnel array and the first hybrid integration with vertical cavity surface-emitting laser array with passive optical alignment using surface micromachining technique. Both the lens array and the VCSEL array stand perpendicular to the substrate, i.e., the optical beams propagate in parallel to the substrate in free space. Therefore, the whole optical interconnect circuits consisting of the VCSEL/lens array source and other similarly fabricated micro-optical elements can be integrated on a single chip. It can potentially be monolithically integrated with the VLSI chips. This novel scheme has applications in board-to-board, chip-to-chip, and intra-chip optical interconnect.

The core element of this scheme is a micromachined micro-Fresnel lens array. The fabrications of both single three-dimensional micro-Fresnel lens and micro-Fresnel lens array have been reported [5], [8]. Micromachined three-dimensional micro-Fresnel lens array is made to stand perpendicular to the Si substrate using micro-hinges and micro-spring latches [9]. In addition, we have also developed novel micromachined three-dimensional alignment structures for incorporating VCSEL array with micro-Fresnel lens array. Integration of VCSEL's and micromachined components is particularly interesting because VCSEL has narrow beam divergence (small numerical aperture) and, therefore, the tolerance of passive alignment relying on the pre-aligned micromachined structures is more relaxed. Additionally, both the micro-Fresnel lenses and the VCSEL's can be made in one-dimensional and two-dimensional arrays. This allows sophisticated free-space optical interconnect scheme be implemented. This approach will greatly reduce the cost, size and volume of free-space optical interconnect systems and other integrated micro-optical systems.

II. Fabrications

A. Micromachining Process

An 8 × 1 micromachined micro-Fresnel lens array has been fabricated using a similar process as the single micro-

Manuscript received January 18, 1995. S. S. Lee was supported in part by a Rand Corporation Fellowship. L. Y. Lin, K. S. J. Pister, and M. C. Wu were supported in part by ARPA ULTRA through Army Research Lab, ARPA NCIPT, and the Packard Foundation.

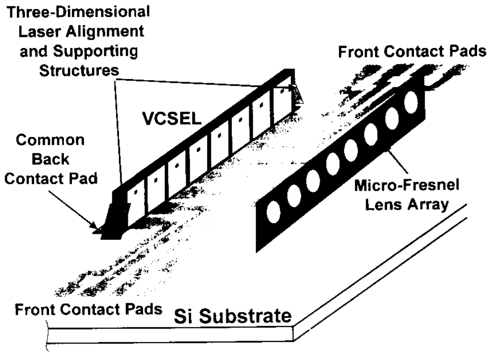
S. S. Lee, L. Y. Lin, K. S. J. Pister, and M. C. Wu are with the Electrical Engineering Department, UCLA, Los Angeles, CA 90095-1594 USA.

H. C. Lee and P. Grodzinski is with the Motorola Inc. Phoenix Corporate Research Laboratories, Tempe, AZ 85287 USA.

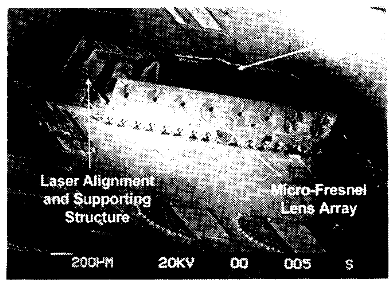
IEEE Log Number 9413492.

1041-1135/95$04.00 © 1995 IEEE

Fresnel lens [5]. First, a 2-μm-thick phosphosilicate glass (PSG) layer is deposited on silicon substrate and serves as a sacrificial layer. Then, the first structural polysilicon layer of 2-μm thickness is deposited on top of the first PSG layer. Part of micro-hinges and micro-spring-latches are defined by lithography on this polysilicon layer. After a 0.5-μm-thick second PSG layer is grown, the second polysilicon layer of 1.5-μm thickness is deposited. The Fresnel zone pattern, side supporting structures, and the rest of micro-hinges and micro-spring-latches are defined on the second polysilicon layer. After selectively removing the PSG layers with HF solution, the micro-Fresnel lens array is freely rotated out of the silicon wafer plane. It is fixed and locked at 90° to the substrate by the micro-spring latches and the side supporting structures. The schematic diagram and the scanning electron micrograph (SEM) of the 8 × 1 micro-Fresnel lens array and the VCSEL array after assembly are shown in Fig. 1(a) and (b), respectively. The micro-Fresnel lens array plate is 2 mm wide and 350 μm tall. The center of the Fresnel zone rings (optical axis) is defined to be 254 μm above the substrate plane. The focal lengths of each micro-Fresnel lens are designed to be 500 μm. Three-dimensional side supporting plates are incorporated to align and support the lens array as well as the VCSEL array. They consist of folded polysilicon plates similar to the lens plate except that their folding directions are orthogonal. The lens supporting plate has a symmetric V-shaped opening tapering down to a 2-μm-wide groove that holds the lens plate precisely at a 90° angle. The mechanical strength is also greatly enhanced. Fig. 2 shows the SEM photograph of the side supporting structure, micro-hinges and micro-spring latches. The VCSEL supporting plate, on the other hand, has an asymmetric U-shaped opening that pushes the side-mounted VCSEL forward into the focal plane. The front edge of the U-opening is flat and pre-aligned with the focal plane. This unique design has the advantage of accommodating VCSEL's of a wide range of substrate thickness.



(a)



(b)

Fig. 1. (a) The schematic diagram and (b) scanning electron micrograph (SEM) of the 8 × 1 micro-Fresnel lens array and the 8 × 1 VCSEL array.

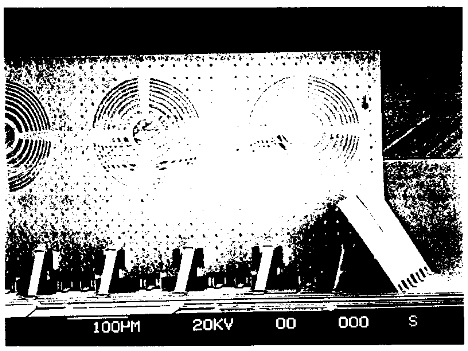
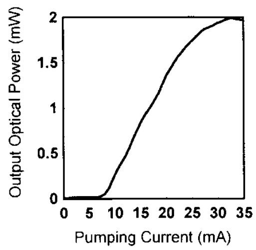


Fig. 2. The scanning electron micrograph (SEM) of the side-supporting structure, micro-hinges, and micro-spring latches.

B. VCSEL

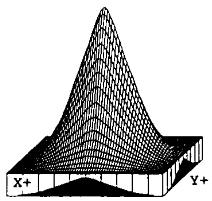
The VCSEL is grown by metalorganic chemical vapor deposition (MOCVD). It consists of a 35-pair n-doped quarter-wave GaAs–AlGaAs bottom distributed Bragg reflector (DBR) stack, three InGaAs–GaAs strained quantum-well active layers, a 25-pair p-doped top DBR mirror, and a P+ GaAs cap layer. The VCSEL operates at 0.95-μm wavelength. The light-versus-current characteristics and the far-field pattern of the integrated VCSEL/lens module are shown in Fig. 3. Typical threshold currents are 8 mA for 20 μm × 20 μm VCSEL's (4 mA for 10 μm × 10 μm VCSEL's), and the maximum output powers are 2 mW. The VCSEL array is 2 mm wide and the spacing between two adjacent VCSEL elements is 250 μm. To match the optical axis of the micro-Fresnel lens array, the VCSELs are precisely scribed into 2 mm × 350 μm chips and the emitting spots are located at 254 μm from the scribed edge. When the VCSEL is mounted on the side, the emitting spots are aligned with the centers of the micro-Fresnel lens array. The mounting and alignment blocks and electrical contacts for each individual VCSEL elements of the array are defined by lithography during the fabrication of the micro-Fresnel lens arrays.

Side-mounting of VCSEL's has many advantages: first, the output optical beam is parallel to the substrate surface, which is compatible with the integrable micromachined optical elements. Second, the optical axis can be precisely defined and match to that of the rest of the integrated free-space optical system. One potential disadvantage of the side mounting scheme is that the thermal resistance might be slightly higher. Therefore, we have compared the lasing characteristics of the VCSEL's with side mounting and conventional junction-side up mounting. Both VCSEL's have comparable threshold



The L-I curve of VCSEL

(a)



3-D beam profile

(b)

Fig. 3. (a) The light-versus-current characteristics and (b) the far-field pattern of the integrated VCSEL/micro-lens module.

currents, quantum efficiencies, and characteristic temperatures ($T_o = 75$ K). This is consistent with our analysis of the thermal resistance.

III. Experiment and Results

After the micro-Fresnel lens array is assembled and locked onto the silicon substrate by micro-spring latches and side supporting structures, the VCSEL array is mounted in the designed slot. The VCSEL and the contact pads on Si are electrically connected by conducting epoxy. Each VCSEL element is individually addressable. We demonstrated the ON-OFF characteristics of this integrated device by individually pumping two different elements of the VCSEL array. In this demonstration, we operated the VCSEL at pumping currents less than 1 mA and below threshold for each VCSEL array element, and the signals are detected by a high resolution CCD camera. The CCD images of the ON-OFF characteristics of two individual VCSEL elements of the array are shown in Fig. 4. Similarly, all eight VCSEL elements can be independently modulated. We believe that this integrated device is suitable for free-space optical interconnect in low-power applications, e.g., internal interconnects for microprocessors.

IV. Conclusion

In conclusion, an 8 × 1 vertical three-dimensional micro-Fresnel lens array has been demonstrated for the first time using micromachining technique. We have also successfully demonstrated a novel scheme to implement free-space optical interconnect using the hybrid integration of the micromachined micro-Fresnel lens array and a vertical cavity surface emitting laser (VCSEL) array with passive optical alignment. They can also be integrated with other similarly fabricated micro-optical elements such as rotatable mirrors, rotatable gratings and beam splitters as well as other passively aligned active micro-optical devices. The ON-OFF switching characteristic is demonstrated by individually modulating two VCSEL/lens elements. The results show that this new technology is very promising for implementing optical interconnect and many other micro-optical systems.

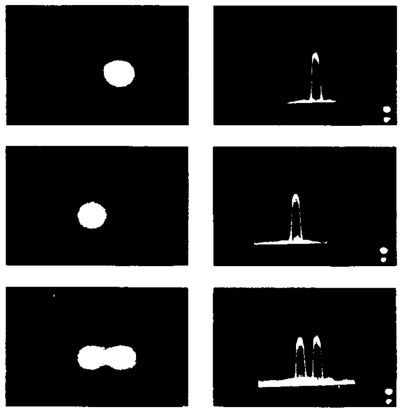


Fig. 4. The ON-OFF characteristics of two individually modulated VCSEL's imaged through the integrated micro-Fresnel lenses.

References

[1] J. W. Goodman, F. J. Leonberger, S.-C. Kung, and R. A. Athale, "Optical interconnection of VLSI systems," in *Proc. IEEE*, vol. 72, no. 7, pp. 850–866, 1984.
[2] A. R. Johnston, L. A. Bergman, and W. H. Wu, "Optical interconnection techniques for hypercube," in *Proc. SPIE-1988*, (Optical Computing and Nonlinear Materials), Los Angeles, CA, Jan 11–13, 1988, vol. 881, pp. 186–191.
[3] T. Sakano, K. Noguchi, and T. Matsumoto, "Novel free-space optical interconnect architecture employing array devices," *Electron. Lett.*, vol. 27, no. 6, pp. 515–516, 1991.
[4] S. Kawai, "Free-space multistage optical interconnection networks using micro lens arrays," *J. Lightwave Technol.*, vol. 9, no. 12, pp. 1774–1779, 1991.
[5] L. Y. Lin, S. S. Lee, K. S. J. Pister, and M. C. Wu, "Three-dimensional micro-Fresnel optical element fabricated by micromachining technique," *Electron. Lett.*, vol. 30, no. 5, pp. 448–449, 1994.
[6] ——, "Micro-machined three-dimensional micro-optics for integrated free-space optical system," *IEEE Photon. Technol. Lett.*, vol. 6, no. 12, pp. 1445–1447, 1994.
[7] K. Rastani, M. Orenstein, E. Kapon, and A. C. Von Lehmen, "Integration of planar Fresnel microlenses with vertical-cavity surface-emitting laser arrays," *Opt. Lett.*, vol. 16, pp. 919–921, 1991.
[8] S. S. Lee, L. Y. Lin, K. S. J. Pister, M. C. Wu, H. C. Lee, and P. Grodzinski, "An 8 × 1 micromachined micro-Fresnel lens array for free-space optical interconnect," in *Proc. Lasers Electro-Optics Soc. 7th Annu. Meet., LEOS '94*, Boston, Oct. 31–Nov. 3, 1994, vol. OS-4.3, pp. 242–243.
[9] K. S. J. Pister, M. W. Judy, S. R. Burgett, and R. S. Fearing, "Microfabricated hinges," *Sensors Actuators A*, vol. 33, pp. 249–256, 1992.