Realization of novel monolithic free-space optical disk pickup heads by surface micromachining

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A novel monolithic free-space optical disk pickup head has been fabricated by micromachined micro-optical bench technology. The pickup head contains a self-aligned semiconductor edge-emitting laser, a collimating lens, a beam splitter, two focusing lenses, and two 45° mirrors. All optical components are built monolithically on Si substrates. The 45° mirror directs the optical output beam in the surface-normal direction. This novel design could significantly reduce the size and the weight of the optical pickup head as well as the cost of the assembly processes. The weight reduction could also greatly increase the data access rate. © 1996 Optical Society of America

Optical data storage has found a rapidly growing market in recent years. It can achieve high areal density and large storage volume with removable media. The design of the optical disk pickup head plays a key role in the performance of an optical storage system. Recently there has been a great deal of interest in the monolithic integration of optical pickup heads. The integration will not only reduce the assembly cost by eliminating bulk optical elements but also enhance the device's performance. Because the optical pickup head is usually placed in a feedback loop to maintain focusing and tracking, lighter heads will lead to higher data access rates.[1]

Two methods of designing integrated optical pickup heads have been proposed: the waveguide approach with focusing gratings[2] and the diffractive planar micro-optics approach.[3] The waveguide approach suffers from high coupling loss, and it is more difficult to fabricate high-performance lenses by using focusing gratings. The planar optics approach requires precision alignment on both sides of the substrate and is sensitive to optical cross talk of high-order diffraction beams. Because the optical pickup head is a free-space optical system, the integration scheme based on free-space optics is more suitable for optical pickup heads.

Previously, we proposed and demonstrated a novel free-space micro-optic bench (FS-MOB) technology, using surface-micromachining techniques.[4] Three-dimensional micro-optical elements with optical axes parallel to the substrate are successfully fabricated. This enables the entire free-space optical system to be integrated on a single chip. The Si substrate serves as a micro-optical bench on which three-dimensional optical elements, micropositioners, and actuators are monolithically fabricated. Incorporation of semiconductor edge-emitting lasers with novel three-dimensional self-alignment structures has also been successfully demonstrated.[5] Here we report what is to our knowledge the first fabrication of a novel monolithic optical disk pickup head that uses the FS-MOB technology. The optical performance is successfully characterized.

Figure 1(a) is a schematic drawing of the free-space optical disk pickup head. It consists of a self-aligned semiconductor edge-emitting laser source, a collimating lens, two focusing lenses, a beam splitter, and two 45° reflectors. The optical axis of the system is designed to be 254 μm above the Si substrate. The laser is mounted on its side with the help of three-dimensional alignment structures[5] so that its emitting spot is aligned with the optical axis. A semiconductor edge-emitting laser with a wavelength of 0.98 μm is used for this demonstration. A shorter-wavelength laser can be similarly incorporated to increase the spatial resolution. First the

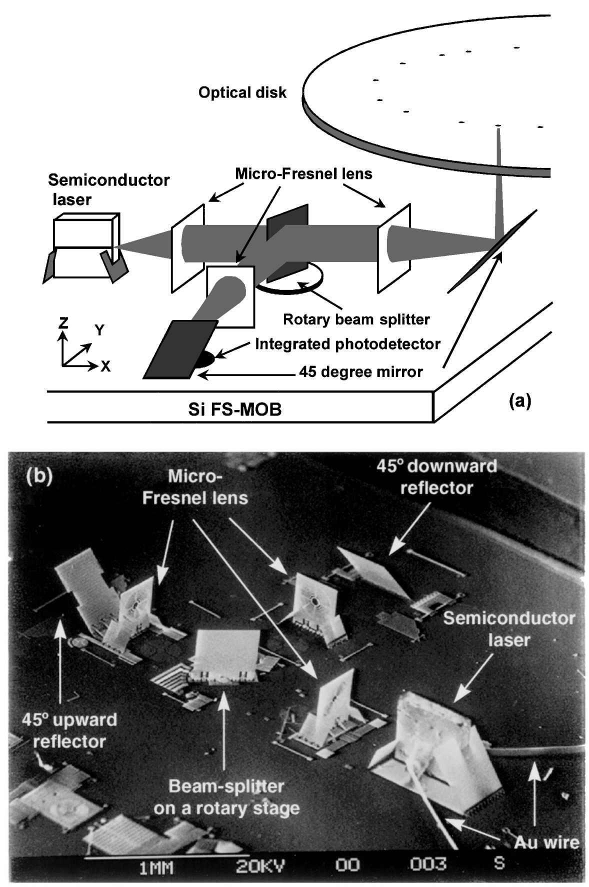

Fig. 1. (a) Schematic and (b) scanning electron micrograph of the free-space integrated optical disk pickup head.

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light emitted from the laser is collimated by a micro Fresnel lens. Part of the collimated beam passes through the beam splitter and is focused by a second micro Fresnel lens. The beam splitter is integrated with a rotary stage that has been rotated by 45°. The light reflected from the beam splitter is used for diagnosis of the beam quality. The focused light is further bent upward by an integrated 45° mirror, which enables the pickup-head chip to be mounted in parallel to the optical disk. This design has several advantages: First, the surface-normal optical access permits wafer-scale testing without the need to separate the individual chips. Second, potentially more than one pickup head can be integrated on the same read–write chip for parallel data access or for simultaneous access of multilayer optical disks. The reflected light from the disk is collected by the same focusing lens, reflected by the beam splitter, and then focused by a 45° downward mirror onto a planar quadrant photodetector built on the Si substrate.

The integrated free-space optical-disk pickup heads are fabricated by microhinge technology[6] with the two-layer polysilicon process. The fabrication process of micro Fresnel lenses and rotary beam splitters was reported in detail in Ref. 4. The fabrication process of the 45° reflecting mirrors is similar to that of micro Fresnel lenses, except for the angle defined by longer microspring latches. Hybrid integration of semiconductor edge-emitting lasers with micro-optics by use of novel three-dimensional self-alignment structures was reported in detail in Ref. 5. The beam splitter is coated with 20-nm-thick Au before the three-dimensional structures are released and assembled. The 45° mirrors and micro Fresnel zone plates are coated with thicker Au. Figure 1(b) shows a scanning electron micrograph of the assembled free-space optical disk pickup head. The Au wires shown attached to the laser are for testing purposes. They can be replaced by lithographic metal lines on Si substrate.

The optical beam profiles at various locations are characterized by a charge-coupled-device (CCD) camera. We measure the collimated beam profile by directly projecting the light reflected from the beam splitter (on the opposite side of the photodetector) onto the CCD camera. The $1/e$-field beam width of the collimated beam versus the distance from the lens is shown in Fig. 2. The divergence angles of the collimated beam are 0.53° in the direction parallel to the Si substrate (X direction in Fig. 1) and 1.8° in the direction perpendicular to the Si substrate (Z direction in Fig. 1). The elliptical shape results from the asymmetric far-field patterns of the edge-emitting lasers. Additional micro-optical elements could be added to correct the beam profile to circular shape.

We measure the focused spot size by imaging the focus to the CCD camera through a microscope. The numerical aperture (N.A.) of the microscope objective lens is larger than that of the focusing micro Fresnel lens, so the spot size is not limited by the measuring optics. We measure the optical beam diameters along the optical axis by varying the focus of the microscope. The distance is measured with respect to a focal plane at which the beam diameter is smallest in the Y direction. The focal plane is at 275 μm above the edge of the 45° mirror. This corresponds to a distance of 875 μm from the focusing lens. Figure 3(a) shows the CCD images of the beam spot at various positions near the focal plane. Relatively large focal depth is obtained because of the small N.A. (~0.17) of the focusing lens in our initial design. The variation of the $1/e$-field beam widths along the longitudinal displacement is shown in Fig. 3(b) for both

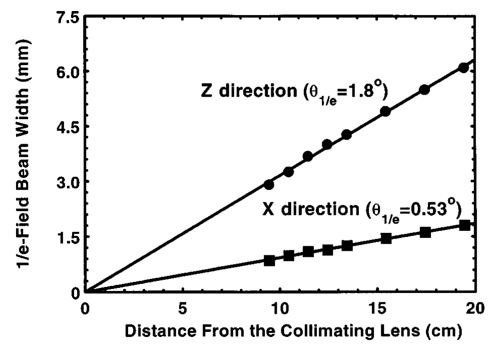

Fig. 2. Widths of the collimated beam versus distance from the lens. The divergence angles of the laser beam emitted from the semiconductor edge-emitting laser have been reduced to 0.53° × 1.8° by the collimating lens.

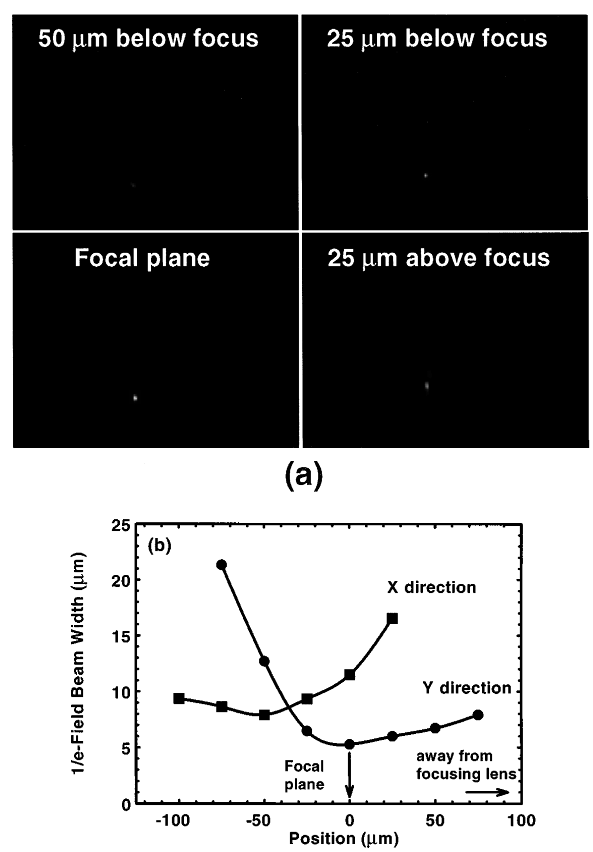

Fig. 3. (a) CCD images of the focused spot near the focal plane. (b) $1/e$-field beam width versus longitudinal displacement near the focal plane. The different focal lengths in the X and the Y directions result from the intrinsic astigmatism of the edge-emitting laser.

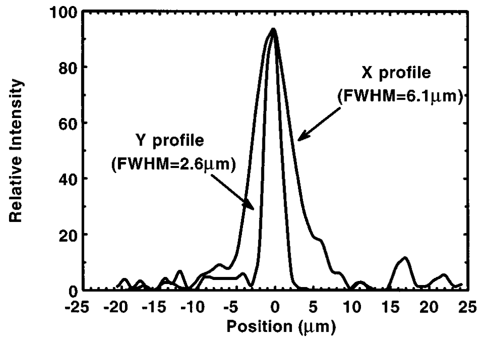

Fig. 4. Optical beam profiles at the focal plane. The FWHM beam widths are 6.1 and 2.6 μm in the X and the Y directions, respectively.

the X and the Y directions. The different focal lengths in the X and the Y directions are attributed to the astigmatism of the ridge-waveguide edge-emitting laser, which is weakly index guided in the lateral direction. Figure 4 shows the beam profile of the focused spot. The full width at half-maximum (FWHM) beam widths are 6.1 and 2.6 μm in the X and the Y directions, respectively. The relatively large spot size is due to the small N.A. of the focusing lens and the long wavelength of the semiconductor laser source used in our first demonstration. One can achieve a smaller focused spot size by employing a focusing lens with a larger N.A., a shorter-wavelength laser source, or both.

In summary, we have fabricated a novel free-space micro-optical disk pickup head monolithically, using the surface-micromachining technique. The pickup head consists of a self-aligned semiconductor laser source and various out-of-plane, three-dimensional free-space micro-optical elements. The integrated optical chip occupies an area of 2.9 mm $\times$ 4.2 mm. The optical performance is successfully characterized. A focal spot with a FWHM size of 2.6 μm $\times$ 6.1 μm is obtained. The integrated optical disk pickup head could significantly reduce the cost, size, and weight as well as improve the performance and access time of optical data storage systems.

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