Verification of a Small-Form-Factor Optical Head With Micro Holographic Optical Element

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A small-form-factor (SFF) pickup head with a holographic optical element (HOE) is fabricated. The system employs a finite-conjugate object lens to focus a light beam. A holographic optical element is used to simplify the optical configuration. It provides a better means of alignment of fabrication and reduces the size of system relative to reflective light route. Thermal analysis was utilized to prove that temperature of LD is under an acceptable range. The pickup head system based on discrete components and a flip chip bonder with highly accurate alignment was to integrate it. Focusing error signal (FES) of pickup head was measured and presented. The optical system is demonstrated and proved that it is a feasible system.

***Index Terms*—HOE, pickup head, SFF, virtual method.**

I. Introduction

A high-density optical disc systems with high-NA objective lenses for small form factor optical head is important to reduce the dimension of optical system. In the past few years, market for optical system such as projector, camera and pickup head grew rapidly and has enhanced the optical system unit with small form to be developed. Miniaturization of optical system has many advantages to achieve light in weight and small in size. There are many miniature way to reduce size, for example, high NA of lens [1] and reflective light route [2]–[6]. Furthermore, micro prisms with inclined process [7] and silicon-based optical element [8], [9] have reliable fabrication process but these device is difficulty to apart from its own substrate to integrated with other optical devices.

A small optical system was designed and simulated by Shih [10] but the study was lacked of systematic fabrication process and entire measurement results. Fabrication process of small optical was designed and implemented to demonstrate light path in expected way. In order to implement the structure and verify optical light route in the small optical system, high bonding precision is utilized to accomplish the FES requirement. Moreover, the holographic optical elements (HOE) have been widely applied to minimize optical system with their particular features in the functions of splitting laser beam. Recently study presents that HOE can be fabricated by silicon substrate with silicon nitride [8], [9] which is compatible with standard semiconductor process, however, thickness of substrate is difficult to minimize size of SFF optical head.

HOE is employed to minimize the dimension of system for a compact structure and simplify the light route. In this investigation, simulation and measurement results are successful implemented and verified.

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TABLE I
SPECIFICATION OF OPTICAL PICKUP HEAD

Item	Correspondence
Image object relation	Finite-conjugate system
Laser wavelength	635 nm
Object NA (laser side)	0.1
Image NA (disk side)	0.65
Focal length	0.525 mm
Clear aperture diameter	1.0 mm
Dimensions	1 mm (H) × 3 mm (W) × 5 mm (L)

II. Architecture of Holographic Optical Element Pickup Head With Small Form Factor

This verification process describes an SFF optical system that is based on the optical specifications in Table I. Structure and photography of the integrated pickup head are presented in Figs. 1 and 2, respectively. The proposed devices are fabricated and tested to demonstrate their unique performances and advantages. A 635 nm wavelength LD is expected to play an important role to construct new holographic pickup structures. Fig. 1 schematically depicts the pickup head including a 635 nm wavelength edge-emitting laser diode (LD), a quadrant photodetector (PD), a 45° turning mirror, two micro prisms (MP1, MP2), a holographic optical element (HOE), a lens module, a silicon substrate with metal interconnections and a piece of PCB substrate. A 635 nm edge-emitting LD chip is the main light source in the optical system. It was bonded a silicon sub-mount with eutectic bonding to improve the thermal release efficiency and establish an interconnection, since the laser is a kind of p-side down edge-emitting laser diode. A PD with a quadrant photo detector is applied to generate FES signals. The mirror and prisms work as reflective optical components to reduce the size of optical pickup head. An HOE is utilized as an optical device to produce diffraction. A lens modulus which comprised a finite-conjugate objective lens and a lens holder is to focus light beam. Fig. 2 displays a photograph of the complete optical system unit. The optical layout of a laser module with the HOE is determined the astigmatic focus detection method. Fig. 3 shows the simulation results of optical pickup head for a symmetric FES (S-curve). It was calculated with (A+C)-(B+D) and simulated by different distance between

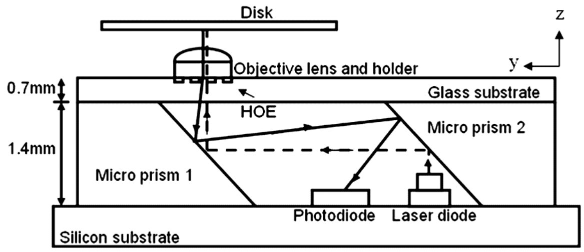

Fig. 1. Structure of micro optical module.

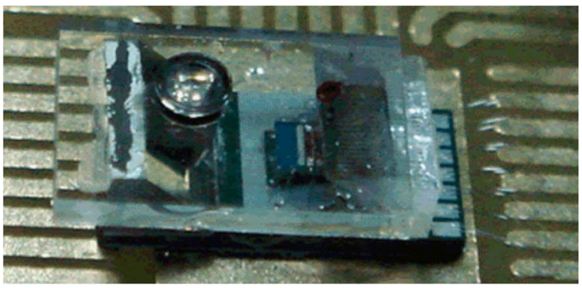

Fig. 2. Photography of small-form-factor optical pickup head.

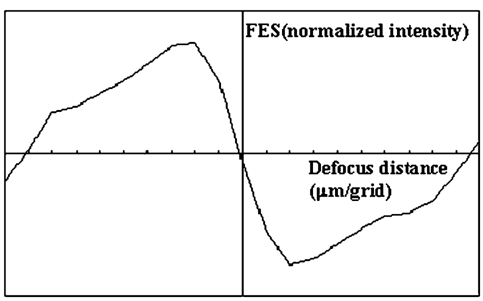

Fig. 3. Simulation result of focusing error signal.

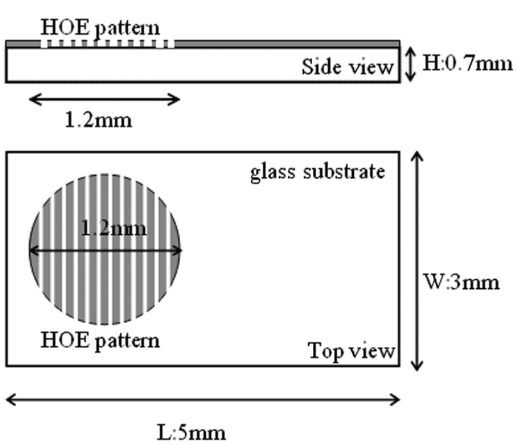

Fig. 4. Structure of holographic optical element.

disk and pickup head. Horizontal and vertical axes are moving distance of disk and calculated results, respectively.

Fig. 4 and Table II show the structure of the fabricated HOE and measurements made of it. It serves as a beam splitter to generate the diffraction beam. An HOE was fabricated on the surface of a glass substrate that was patterned by ICP etching with a depth of 352 nm. For the first order of diffraction, the measurement angle was 12% and the efficiency was 18%.

TABLE II
PERFORMANCE OF HOLOGRAPHIC OPTICAL ELEMENT

	Diffraction angles		Diffraction efficiency	
	Calculated	Measured	Calculated	Measured
Zero order	0°	0°	40%	38%
First order	12.5°	12°	20%	18%

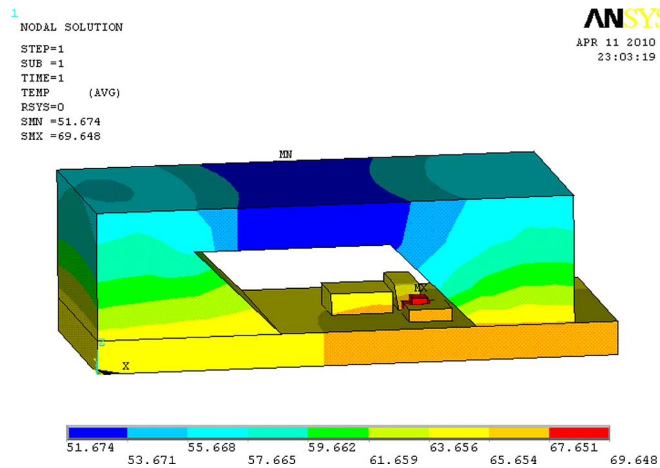

Fig. 5. Thermal analysis of optical pickup head.

TABLE III
THERMAL PROPERTIES RELATED TO HEAT TRANSFER SIMULATION

Material	Density (Kg/m3)	Specific heat (J/Kg K)	Thermal conductivity (W/mK)
Silicon	2330	712	148
Glass	2640	800	1.09
GaAs	5320	330	550

III. THERMAL ANALYSIS OF OPTICAL PICKUP HEAD

A small LD $(250 \times 350 \times 100\ \mathrm{um}^3)$ is made by GaAs and it is a kind of III-V materials. Submount was fabricated with silicon substrate and appropriate thin films were deposited for eutectic bonding. Positive side of LD was integrated on submount with eutectic bonding for signal connection and heat sink. Interconnections bonding area were deposited and patterned on reference substrate.

Thermal analysis of pickup head was presented in Fig. 5 and is used to realize that thermal distribution of pickup head. Heating source of pickup head was generated by LD. Thermal release path is from LD to silicon substrate and interface between each components are metal and high thermal conductivity adhesive. Glass is the main material of micro prisms, turning mirror and diffraction substrate, however, it does not affect the thermal simulation results due the influence of thermal dissipation is silicon substrate. The properties of those materials are list in Table III.

Operational current is 35 mA to drive a 10 mW red ray LD. In order to match specification of pickup head, temperature of LD must be under 70°C. Therefore, the acceptable power was calculated and simulated. The finite element (FE) models with tetrahedral meshes were prepared to analyze the feature of heat transfer in the pickup head. Mesh size and shape were controlled effectively to match the component's characteristics. Small parts of the system, including LD and sub-mount, were divided by fine mesh, whereas the others were divided by coarse mesh. The FE model is made of 226,078 elements for the structure because more elements will not affect the simulation results. The highest temperature is 69.648°C and it is under the specification 70°C. Simulation condition of input power is 230 mW, initial temperature is 25°C and convectional coefficient is 25 m^2K.

IV. Laser Diode Bonding

Optical components manipulate light to the desired location and the most important operation during the assembly of the SFF pickup is the precise attachment of a temperature-sensitive laser diode. The threshold current and operating temperature crucially affect LD lifetime because increasing the operating temperature increases threshold current. Since SFF size constraints limit heat convection, heat transfer phenomena and other thermal conditions must be considered in system design. An edge-emitting LD operating at a high operating current depends on a heat sink between the active region of the device and the silicon substrate. The high thermal conductivity of a thin film of metal-dielectric enables its use in diode sub-mount applications.

The distance from the edge of the sub-mount to the LD emitting diode is a key factor in the fabrication process of diodes that are mounted with the downward bonding of their p-sides. In the high precision eutectic process, the LD emitting edge must be placed within a few microns outside the edge of the sub-mount. The laser beam is emitted at an angle from the p-side of the laser diode and the space outside the edge of the sub-mount does not reduce the brightness of the emitted laser because nothing blocks the angle of emission. Conversely, if a diode is bonded too far away from the edge of the sub-mount, then the generated heat may reduce its optical performance. To maximize the lifetime of the laser diode, the laser emitting orientation must be properly aligned with the edge of the sub-mount. The laser subassembly must be precisely positioned in relation to other components along the optical axis.

V. Fabrication and Calibration of Optical Pickup Head

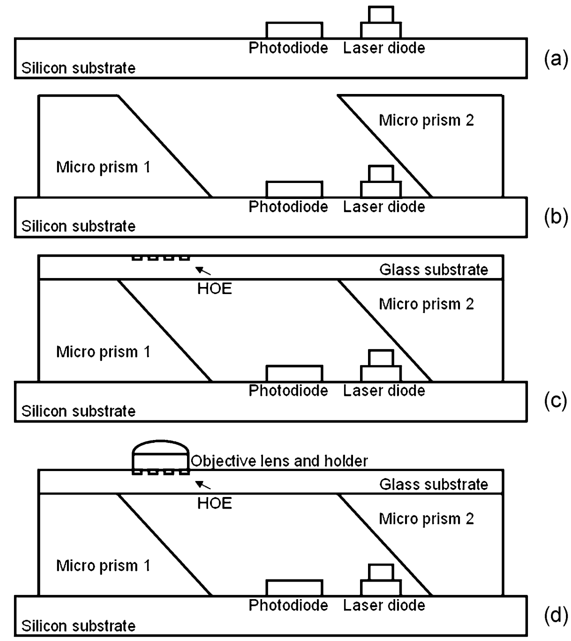

Fig. 6. Fabrication processes (a) Laser diode and photodiode. (b) Turning mirror and micro prisms. (c) HOE glass substrate. (d) Lens modulus.

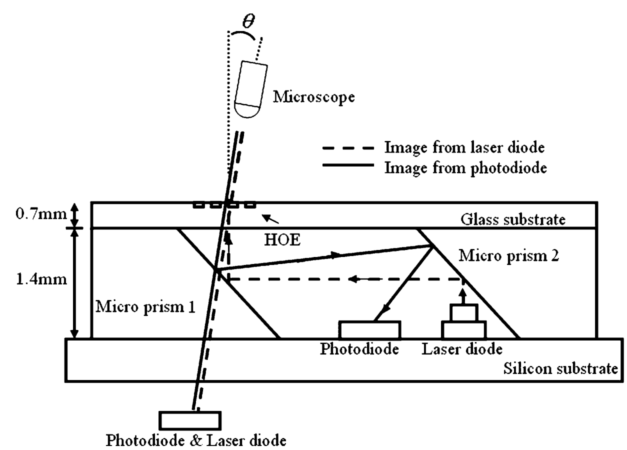

Fig. 7. Virtual image method for calibration and adjusting.

Fig. 6 displays the fabrication process of a small optical system. Firstly, a LD and a PD were bonded onto the substrate that had a patterned metal interconnection. Wire bonding was then implemented to control the driving current and acquire a signal. The mirror and micro prisms were also bonded on silicon substrate to reflect light to reduce the size of system relative to optical pickup head. A glass substrate with an HOE was bonded to both of prisms, such that the light path could be calibrated with virtual image method. The final step in fabricating the optical system was the bonding of the lens modulus to the surface of the HOE.

The virtual image method was used to calibrate an optical system with a high-precision alignment. To reflect light to the center of the quadrant photodiode, an alignment procedure can be performed to adjust the relative positions of the photodetector and the HOE, as in Fig. 7. The virtual image of the laser is obtained by extending the diffracted beam to the virtual focal image, which must coincide with the location of the photodetector image. Since the HOE and the other integrated unit were aligned with virtual image method in the established light path, optical alignment was conducted by replacing micro prism 1 and the HOE glass to calibrate the lateral and circular displacement of system layout in a specific fixture apparatus with a tilted angle. The fixture apparatus is applied to setup experiment of virtual image method and the optical pickup head is fastened on it to calibrate its tolerance. Therefore, alignment tolerances among the LD, turning mirror, and micro prisms assembly are eliminated and the precision of light path that begins at LD and is reflected to the center of PD is ensured in the small optical system.

Fig. 8 presents virtual images of calibration obtained with various focal points. The light spot is focused and defocused on the center of the quadrant detector repeatedly. The method of calibrating is astigmatic returning method and the simulated spots are presented for comparison with actual measured result.

After the micro prisms and the HOE were attached to the optical module, the objective lens unit was the final component to be assembled. A mechanical xyz stage was utilized to assemble the objective lens unit on the optical module to minimize aberrations such as coma, astigmatism, and spherical aberration.

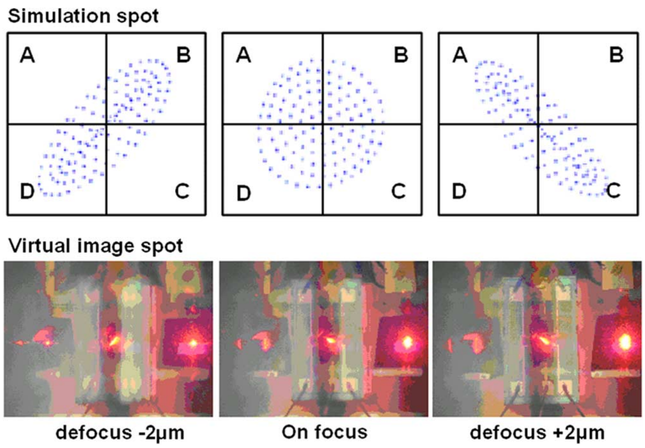

Fig. 8. Calibration light spot of virtual image method.

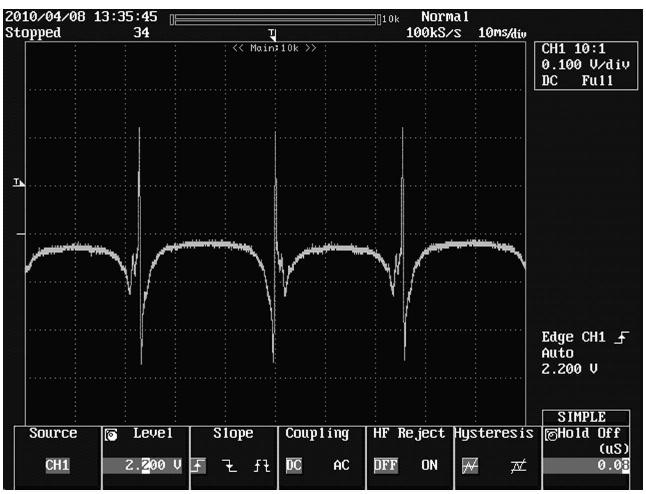

Fig. 9. Measurement of focusing error signal (S-curve).

VI. Experimental Results

Fig. 9 presents the symmetrical FES that was obtained by the astigmatic focusing method. The horizontal axis represents defocus position, and the vertical axis represents optical output power. The output signal is calculated as (A+C)-(B+D), and detected by the quadrant detectors. To verify the focusing performance of this HOE optical module, the focusing actuator was driven by a 5 Hz triangular signal with amplitude of $\pm$140 mV to bring the optical module past its focal point to the disc. A comparison of the simulated results and dynamic experimental data reveals that the measured results were satisfactory and demonstrated the feasibility of the SFF pickup head.

VII. Conclusion

This study proposes a new optical pickup head with small form factor, with a demonstrably feasible fabrication process. The small optical system has height, width and length of $1\ \mathrm{mm} \times 3\ \mathrm{mm} \times 5\ \mathrm{mm}$. The pickup head system using existing discrete components was demonstrated, and a flip chip bonder with highly accurate alignment was to integrate it. The SFF pickup with the HOE was fabricated to meet optical specifications to simplify the optical architecture and minimize the scale of the device. To ensure that the optical system performs reliably, the temperature-sensitive laser diode must be accurately assembled with a silicon sub-mount which has a high capacity for thermal release. After the reference optical path was established, the virtual image method with HOE pattern alignment was performed to achieve an optical configuration. Finally, the experimental result of FES was presented that light path or SFF are demonstrated. This integrated SFF pickup head with HOE is a feasible for use in next-generation optical storage systems.

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