Fabrication and Verification of a Small-Form-Factor Blue-Light Optical Pickup Head With Holographic Optical Element

Yue-Jheng Lin, Yi Chiu, Hsi-Fu Shih, and Jin-Chern Chiou, *Member, IEEE*

***Abstract*—A small-form-factor (SFF) blue-light optical pickup head (OPH) with holographic optical element (HOE) has been fabricated and assembled. The assembly and alignment of various components in the pickup head were facilitated by using a flip chip bonder. Experimental results indicated that the focusing error signal (FES) of the assembled OPH with the wavelength of 405 nm could be successfully detected. The linear range of the FES was about than 4 μm. The gauge repeatability and reproducibility (GR&R) of the assembly process was tested and found to be acceptable.**

***Index Terms*—Blu-ray, gauge repeatability and reproducibility (GR&R), holographic optical element, optical pickup head, small-form-factor (SFF), virtual image method.**

I. INTRODUCTION

In recent years, small-form-factor (SFF) and high recording capacity is the basic requirement for the information-technology products. A major concern in the optical pickup head (OPH) today is to continuously reduce the form factor and increase the recording density. Previous studies, such as [1]–[9], indicated that the size of OPH was determined by the light path and could be reduced by using micro optical elements. Shih [10], [11] designed a novel SFF OPH but did not implement the device. Our previous studies [12], [13] successfully realized Shih's design with a red laser. Nevertheless, blue laser is used in the Blu-ray format in the next-generation optical storage to increase the recording density. Therefore this paper reports the fabrication and verification of a SFF OPH in the 405 nm wavelength based on the design in [11].

TABLE I
SPECIFICATION OF THE OPH

Parameter	Specification
Image-object relation	finite-conjugate system
NA	0.65
Laser wavelength	405 nm
Object NA (laser side)	0.1
Image NA (disk side)	0.65
Focal length	0.670 mm
Clear aperture diameter	1.1 mm
Dimensions	3.1 mm (H) × 4 mm (W) × 9 mm (L)

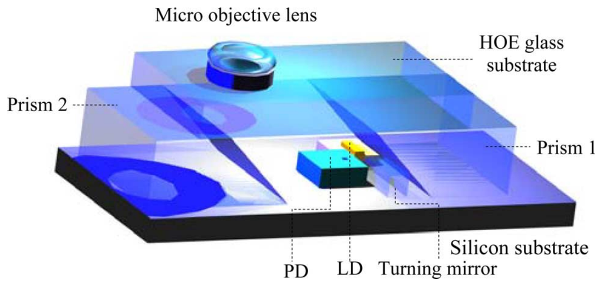

Fig. 1. OPH system.

The specification of the current SFF OPH is listed in Table I. Compared to the red OPH in [12], [13], the objective lens was redesigned in the blue wavelength. In addition, the dimensions of the OPH were adjusted according to the chip size of available blue laser diodes. The OPH was assembled by using a flip chip bonder. To ensure the accuracy and precision of the assembly process for mass production, the gauge repeatability and reproducibility (GR&R) was tested and found to be acceptable.

II. FABRICATION OF INTEGRATED OPTICAL PICKUP HEAD

Fig. 1 shows the schematic of the OPH. The optical power source is a P-side-up edge-emitting laser diode (LD) with a wavelength of 405 nm. A quad photodetector (PD) (see Fig. 2) is used to detect the reflected data and servo signals. The size of the PD segments is $50 \times 50\ \mu\mathrm{m}^2$ and the spacing between segments is 5 μm. The specification of the PD is shown in Table II. A 45° micro turning mirror and two 45° prisms are used to reflect and fold the optical path for a compact optical design. The holographic optical element (HOE) (Fig. 3) plays a key role to reduce the complexity and dimensions of the OPH module. When the

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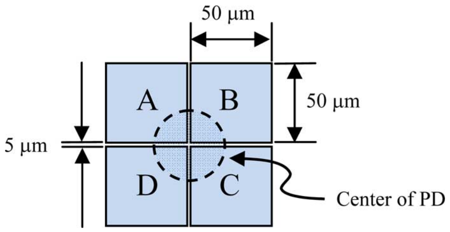


Fig. 2. Quad photodetector.

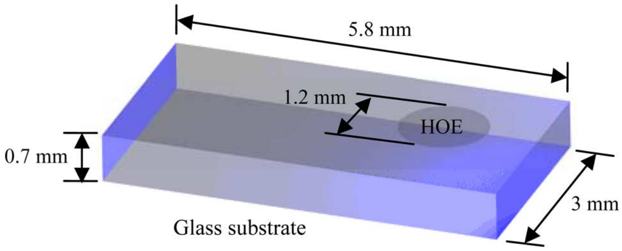


Fig. 3. Structure of HOE.

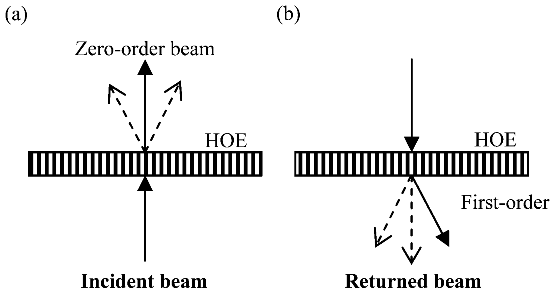


Fig. 4. (a) Incident beam from LD. (b) Reflected beam from disk.

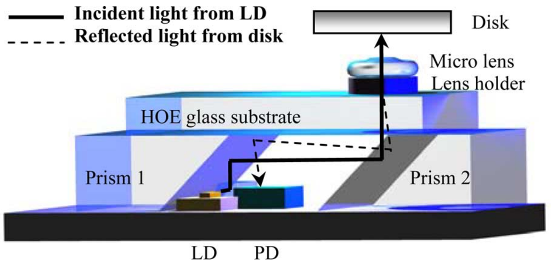


Fig. 5. Optical path of OPH.

TABLE II
SPECIFICATION OF PHOTODETECTOR

Parameter	Specification
PD segment size (μm × μm)	50 × 50
Breakdown voltage (V)	> 10
Sensitivity (A/W)	> 0.2 (405nm)
Dark current (nA)	< 2
Crosstalk (%)	15 (gap 5μm)
Rise time & fall time	5 ns for center detecting elements

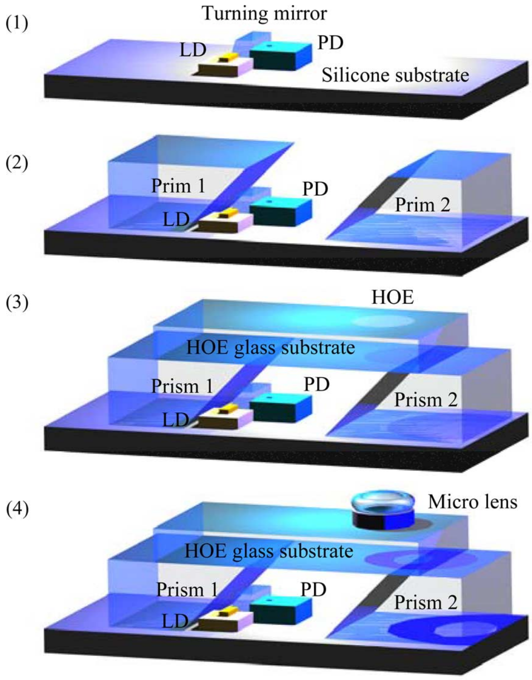


Fig. 6. Fabrication process of the OPH.

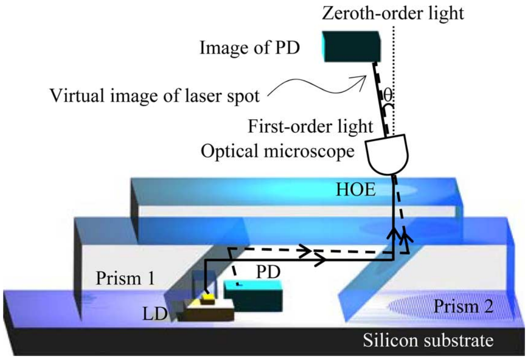
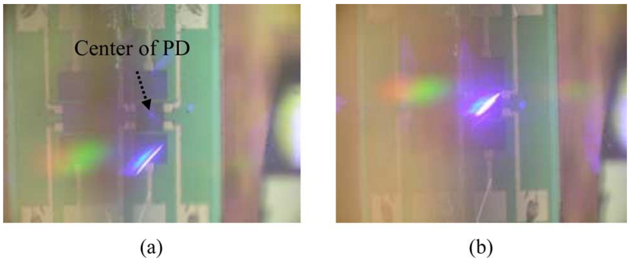


Fig. 7. Virtual image method for the optical path alignment.

incident light passes through the HOE, the zeroth-order beam is focused on the disk by the micro objective lens to detect the signal [Fig. 4(a)]. In the return path, the first-order beam is diffracted by 7.5° and incident on the PD [Fig. 4(b)]. Therefore the PD and LD can be separated by a small displacement to keep the optical system compact. The optical path is shown in Fig. 5.

The simplified assembly process of the OPH is shown in Fig. 6 and described as follows. A flip-chip bonder was used to place and align the optical components. 1) The LD, PD and micro turning mirror were assembled onto the silicon substrate. 2) Prism 1 and Prism 2 were attached on the silicon substrate. The prisms and mirrors all had anti-reflection coating for 405 nm. 3) The HOE was first fabricated on a 0.7-mm Corning E2K glass substrate which had a transmission of 92% at 405 nm to reduce the absorption loss. The glass substrate was then bonded upon the two prisms. The virtual image method [14] was used to align the optical path by observing the virtual image of the first-order diffracted laser spot overlapped with the image of PD at the angle of diffraction (7.5°) (see Fig. 7). The position of the HOE was adjusted to compensate for the alignment and assembly errors until the first-order light was in the center of PD. Fig. 8 shows the overlapped images before



(a) (b)

Fig. 8. Adjusting the HOE position to compensate for the alignment error. (a) Before alignment. (b) After alignment.

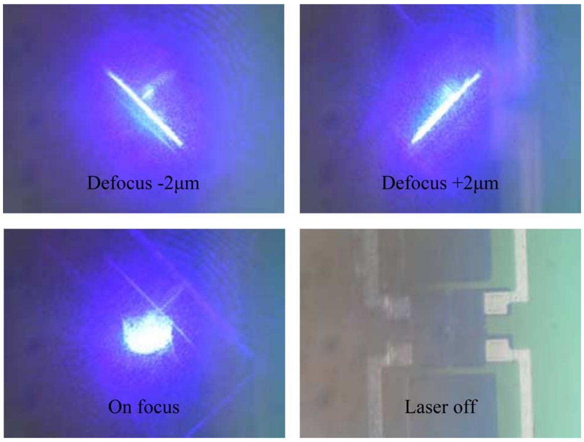


Fig. 9. Virtual images in various focal conditions.

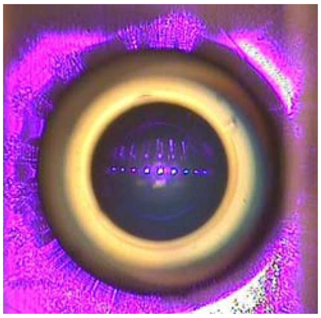


Fig. 10. Micro lens accurately aligned with the diffracted optical beams and bonded on the surface of HOE.

and after adjusting the HOE. This method can be used to compensate for the assembly error if the initial laser spot is within 200 μm from the center of PD. Fig. 9 shows the virtual astigmatic images of the correctly aligned spot in various focus conditions. 4) Finally, the micro lens was bonded on the surface of the HOE glass substrate with the laser spots aligned to the center of the lens (see Fig. 10).

III. EXPERIMENTAL RESULT

The final assembled blue-light OPH with holographic optical element is shown in Fig. 11. The dimensions of the complete OPH are 3.1 mm (H) × 4 mm (W) × 9 mm (L). The OPH uses the HOE to split the return beam from the incident beam to reduce the dimensions of the module. The measured diffraction efficiency of the zeroth- and first-order beams is 66% and 9%, respectively. The efficiency of the diffraction orders are designed to maximize the reflected optical power on the PD. In the experiments, the minimum power of the 405-nm laser diode was about 10 mW in order to have enough signal-to-noise ratio in the detected signal. The fabrication errors of the HOE affect the signal power and diffraction angle. From the simulation, the signal power reduction caused by the error in grating depth and linewidth can be compensated for by increasing the amplifier gain if the error is within 10% of the design values. The error in the grating period causes erroneous diffraction angle. It is estimated that a 2% period error causes a shift of the laser spot on the PD by about 13 μm, which can be recovered by adjusting the position of the HOE, as shown in Fig. 8.

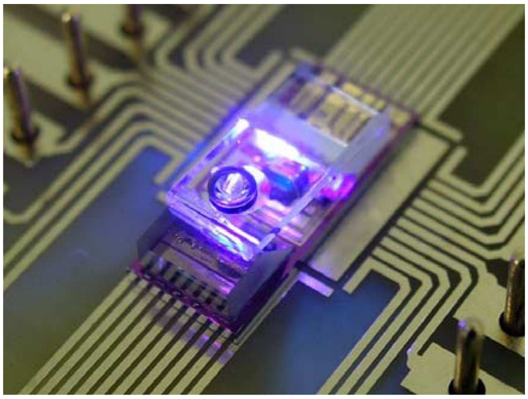


Fig. 11. Assembled SFF blue-light OPH with HOE.

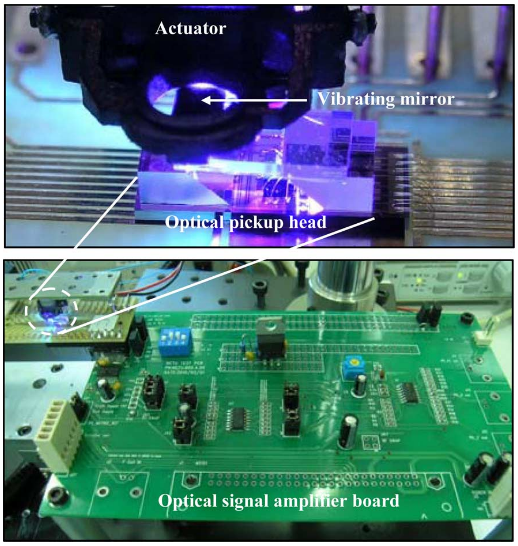


Fig. 12. FES (S-curve) measurement platform.

Fig. 12 is a platform used to measure the focus error signal (FES) (S-curve). It has a voice coil motor (VCM) and a signal processing and amplification board. The VCM was driven by a 5-Hz sine signal with amplitude of 140 mV. A micro mirror was attached to the VCM to reflect focused light of the OPH back into the quad PD to measure the S-curve by calculating the FES as $(\mathrm{A}+\mathrm{C})-(\mathrm{B}+\mathrm{D})$. The measured S-curve is shown in Fig. 13. The linear range of the FES is about 4 μm. The S-curve in Fig. 13 is not entirely symmetric due to a tiny shift of the reflected laser spot with respect to the center of PD. If an automatic pick-and-place bonding system with accurate robotic arms and

TABLE III
GR&R MEASUREMENT

Operator	A				B				C			
Sample No	1st Trial	2nd Trial	3rd Trial	Range	1st Trial	2nd Trial	3rd Trial	Range	1st Trial	2nd Trial	3rd Trial	Range
1	13.25	13.86	12.00	1.86	17.00	18.95	15.87	3.08	13.57	13.10	12.48	1.09
2	14.04	11.94	14.48	2.54	13.90	13.63	14.77	1.14	13.59	12.57	14.17	1.60
3	5.38	7.85	6.79	2.47	4.60	6.11	5.46	1.50	8.14	5.97	7.00	2.17
4	17.49	14.34	15.26	3.15	11.31	10.89	14.66	3.77	13.88	13.05	15.18	2.13
5	13.72	13.28	12.47	1.25	15.92	15.46	13.98	1.94	13.12	16.11	15.15	2.99
6	13.88	12.22	13.41	1.66	14.95	14.58	11.94	3.00	16.30	15.50	15.02	1.29
7	10.38	8.77	8.77	1.62	8.40	11.49	10.11	3.09	10.72	9.60	10.15	1.12
8	26.22	29.10	26.98	2.88	24.44	21.81	23.23	2.63	25.89	25.88	25.49	0.40
9	12.01	9.75	12.37	2.62	14.45	14.77	13.57	1.20	12.18	12.49	12.20	0.31
10	13.43	13.15	14.53	1.39	15.82	16.11	14.03	2.08	14.35	19.00	14.93	4.65
			$\overline{R}_a$	2.142			$\overline{R}_b$	2.344			$\overline{R}_c$	1.775
			$\overline{X}_a$	13.704			$\overline{X}_b$	14.074			$\overline{X}_c$	14.226

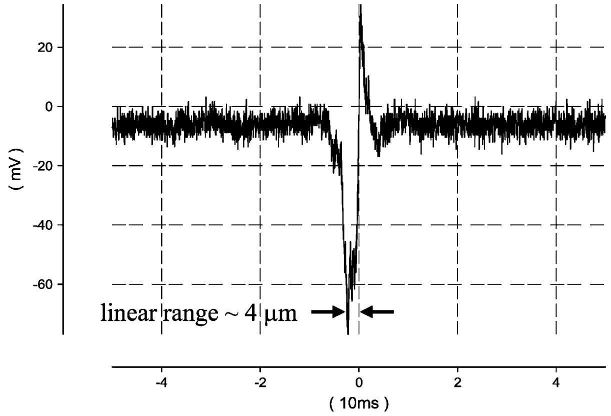


Fig. 13. Measured S-curve.

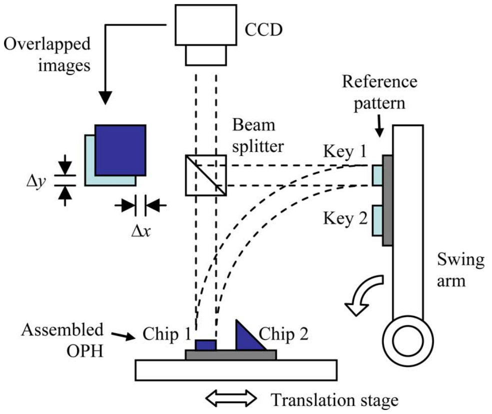


Fig. 14. Measuring the alignment error using the flip chip bonder.

active alignment and tracking control system is available to assemble the optical module, the reduction of assembly and alignment errors and improvement of the S-curve symmetry can be expected. Nevertheless, the optical design and fabrication processes of the blue SFF OPH have been verified experimentally in this work.

To further investigate the quality and stability of the assembly processes of the OPH, a methodology was developed to measure the alignment errors of the assembled components in the module. The flip chip bonder used to assemble the module has a swing arm and a translation stage. The objects on the arm and the stage can be viewed simultaneously by using a beam splitter, as shown in Fig. 14. A reference pattern with keys showing the ideal positions of components can be designed so that the actual assembled module can be compared with the reference pattern in this apparatus to measure the assembly error. In Fig. 14, for example, the component Chip 1 in the assembled module is compared to the corresponding Key 1 in the reference pattern. The assembly errors in both directions can thus be measured from the mismatch of the overlapped images. Table III shows the detailed measurement data of the assembly error of a test component. Ten samples were given to three operators; each sample was measured three times according to standard operation procedures (SOP). The mean of the measurement $\bar{X}$ and range $\bar{R}$ can be calculated as shown in Table III. From $\bar{X}$ and $\bar{R}$, the equipment variation ("Repeatability") is 6.365 μm and the operator variation ("Reproducibility") is 1.407 μm based on three operators and three trials. For a ±20 μm tolerance for this particular component, the percentage GR&R is 16.3%, which is acceptable from the mass production viewpoint. Therefore, by using the systematic assembly processes, we have verified the functionality of the SFF OPH and demonstrated the robustness of the fabrication and assembly processes.

IV. CONCLUSION

In the present study, a small-form-factor blue-light optical pickup head with holographic optical element was demonstrated. A systematic assembly process for the optical head has also been developed. The experimental results verified that the blue-light OPH could successfully detect the focus error signal. The linear range of the S-curve was about 4 μm. The robustness of the assembly process was tested; the percentage gauge repeatability and reproducibility was 16.3%, which was acceptable for mass production. This work can be applied to the batch fabrication of SFF OPH using MEMS techniques [15] to reduce cost and enhance yield and reliability in the next-generation optical storage systems.

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