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Astigmatic diffractive optical element for swing-arm-type optical pickup head

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Abstract. Based on a finite-conjugate objective lens with numerical aperture of 0.62 for a 650-nm wavelength, an optical pickup head composed of a multifunction beamsplitter and a diffractive optical element is designed be used in a swing-arm-type optical pickup head. The diffractive optical element is a lens with an elliptical four-level phase profile to provide both focusing and astigmatism. It is also designed with the goal to simplify the overall optical configuration and provide linear characteristics for the focus error signal. [DOI: 10.1117/1.3158944]

Subject terms: diffractive optical element; actuator; optical pickup head; swing arm.

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1 Introduction

In recent years, the market of mobile devices such as digital cameras and personal digital assistants (PDAs) has expanded rapidly. The trend also enhances the development of the optical drive with small form factors,[1–5] such as the DataPlay (Longmont, Colorado) optical drive. To achieve the right size for such applications, one of the methods is to develop a much thinner optical pickup head using more smart mechanical components and diffractive optical elements, which require more laborious assembly. Thus, it is indispensable to consider the feasibility of assembly in the design stage.

An optical module for this small-form pickup head that is mechanically actuated by a rotary swing arm[6] possesses more favorable features in the assembly.[1] Its main feature is that the function of dynamic motion in an optical drive is achieved by the rotary swing arm, while the optical function is provided by the optical module. The process to make the optical module is usually complicated. To reduce process complexity, the swing arm and the optical module are often fabricated separately and assembled together in the final stage.

In this work, we propose a smart optical module to be applied in a swing-arm-type pickup head. The prototype is a finite-conjugate micro-optical system, which is designed to include a laser diode (LD), a photodiode (PD), a 45-deg beamsplitter, and a holographic optical element. The use of the diffractive optical element (DOE) not only minimizes the number of optical components for a compact structure, but also simplifies the fabrication and light path.

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2 System Description and Analysis

To apply DOEs in a micro-optical system, the challenge is from its optical efficiency being limited to the available quantized levels and minimum linewidth. The total efficiency of the pickup is therefore reduced in general as the number of DOEs and micro-optical elements increases. To enhance efficiency, a finite conjugate system[7] with fewer optical elements can be adopted.

The material used to make the DOE also plays a key role. In the case of polysilicon-based microfabrication technology,[8] the optical performance suffers from high curvature due to the residual stress between the polysilicon frame and the optical film itself. The issue can be solved by using a thicker and stressless single crystal silicon frame to replace the polysilicon one. This concept would be applied in our micropickup, of which the optical configuration based on the parameters listed in Table 1 was used. The material of the DOE is silicon nitride, which possesses high transmission in 650 nm and lower residual stress. The objective lens is obtained from a commercial company. The reason is that fabricating a SiN diffractive element with numerical aperture $(\mathrm{NA}) > 0.5$ requires a minimum linewidth of 0.3 μm, which is beyond the capability of current etching tools. The optical performance of aspherical surfaces in both sides of a conventional objective lens cannot be fully realized using a single diffractive element, which also induces optical aberration.

The schematic diagram of the optics is shown in Fig.

Table 1 Design parameters.

Item	Correspondence
Image-object relation	finite-conjugate system
Laser wavelength	650 mm
Object NA (LD side)	0.15
Image NA (Disk side)	0.62
Total track	10.4 mm
Clear aperature	1 mm
Size	~120 mm^3
Optical components	5
Number of reflections	2
Number of transmissions	4

1(a). It combines the advantages of the design flexibilities of the surface micromachined-type pickup[8] and the simple fabrication of the stacked-type pickup.[9] The whole structure consists of one glass, two general wafers, and one silicon-on-insulator wafer (SOI). The optical devices include a laser diode, a photodiode, a 45-deg upward beamsplitter, a hologram, and a refractive objective lens.

In the forward optical path, the beamsplitter can be used to direct the incident light to the objective lens and the disk. In the backward optical path, the beamsplitter is half-transmissive. The DOE is used to produce an asymmetrical spot on the photo diode, which monitors the focusing status on the disk. Compared with a conventional optical pickup, the required optical elements are significantly reduced. The DOE can be realized on a flat wafer with its back side being etched using bulk etching, so no HF release procedure is required. The beamsplitter is composed of a silicon nitride film mounted on a single-crystal silicon frame to reduce the curvature and enhance transmission. The specification obtained from ZEMAX (Bellevue, Washington) is shown in Fig. 1(b). The simulation result also shows that the dimension of the pickup is feasible using the current fabrication

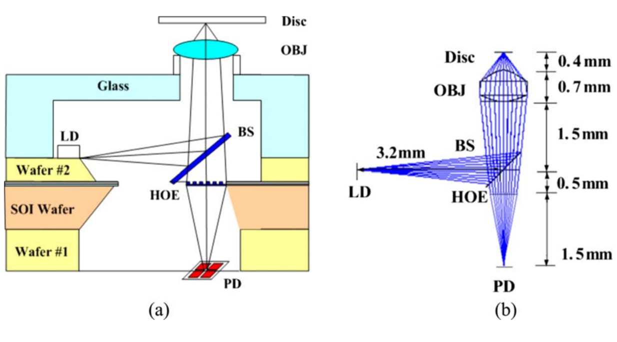

Fig. 1 A surface-micromachined optical pickup based on (a) the finite conjugate design and (b) its specification according to ZEMAX.

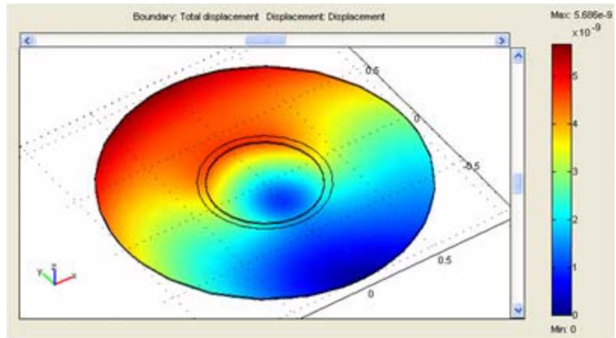

Fig. 2 FEM shows that the deformation of the beamsplitter is below $5.6e^{-3}$ μm.

tools. The tolerance tilt of the 45-deg upward beamsplitter is 0.08 deg, which is achievable using stacked bonding technology.

There are several favorable features in our design. First, the 45-deg upward beamsplitter is used to replace the function of the beamsplitter and the 45-deg upward mirror of the conventional design. In this way, the optical elements can be reduced. Second, a 5-μm silicon frame is provided by a SOI wafer. Since most optical elements are attached within the thick silicon frame, the curvature can be reduced. Finite element method (FEM) simulation shows that the deformation of the beamsplitter with a 500-μm diameter is below $5.6e^{-3}$ μm, as shown in Fig. 2. Under such conditions, the optical performances of the beamsplitter and DOE remain good. Third, no laborious assembly is required. Since only the 45-deg upward beamsplitter needs to be assembled, the yield of the new design can be enhanced, compared with the previous design in Ref. 8. Fourth, there are no etch holes and dimples in the optical pattern, which induces no optical noise. To help release, a back side bulk etching is designed. All etch holes are defined in the side latches, as shown in Fig. 3.

3 Diffractive Optical Element Design and S-Curve

An optical disk usually has a plastic substrate that is not perfectly flat but slightly warped. When mounted in a drive,

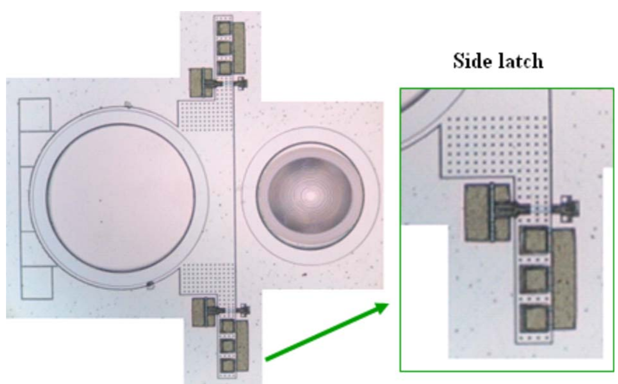

Fig. 3 Photograph of the smart mask design. The etch holes concentrate on the side latches.

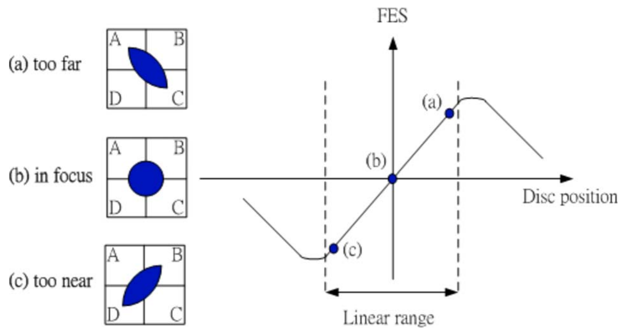

Fig. 4 Variation of a focal spot and its corresponding S-curve. (a) Disk surface is far from the objective lens, FES>0. (b) Disk surface is in focus of the objective lens, FES=0. (c) Disk surface is near to the objective lens, FES<0.

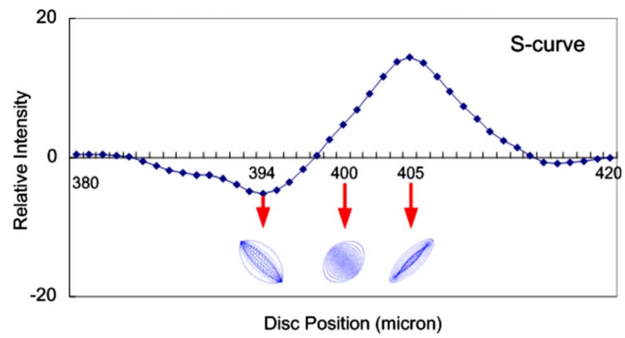

Fig. 5 Simulation result of focus error signal.

small tilts of the axis could cause vertical motions of the disk surface as much as 100 μm during operation.

In our system, the optical pickup is designed for a swing-arm actuator (bandwidth of several kilohertz), which can be used to maintain the disk continually on focus of the focused beam from the pickup under a feedback mechanism. The relative distance between the objective lens and the surface of the disk can be monitored by an astigmatic focus-error detector, which provides such feedback focus error signals (FESs). To generate a FES, the DOE is used to focus on a four-quarter photodiode (PD), which is 1.5 mm below the DOE, as shown in Fig. 1(b). Due to the vibration and wobbling of the disk, the objective lens cannot always exactly project its focus spot on the data surface of the disk. In the backward optical path, the focal spot on the PD is therefore moved because of the optical properties of the DOE, as can be seen in Fig. 4. In perfect focus, the focal spot is equally distributed on the four segments of the PD with the signal combination $(A+C)-(B+D)=0$. If the disk position is in front of the focal point of the objective lens, the signal combination is $(A+C)-(B+D)<0$. If the disk position is behind the focal point of the objective lens, the signal combination is $(A+C)-(B+D)>0$. The unequal distribution of the spot on the PD generates a curve of $FES=(A+C)-(B+D)$, which is often called the S-curve because of its shape. The curve reflects the position of the disk.

Since our system is finite conjugate, the light reflected from the disk and collected by the objective lens is convergent, whether the disk is farther away from best focus or closer to the lens than the plane of best focus. Therefore, our DOE is an elliptically shaped DOE. A similar DOE has been demonstrated by Leger, Scott, and Veldkamp.[10] They describe the use of a lenslet array made of diffractive elements that couples together the output of many laser diodes in a linear array. Elliptical DOEs were used to compensate for the astigmatism in the output of the individual diodes. In our design, the DOE possesses convergent and astigmatic function instead of pure astigmatic function. The pattern is designed by binary optics technology and has the wavefront represented by

$$\phi=\sum_{i=1}^{n}\sum_{j=1}^{n}A_{ij}x^{i}y^{j}, \tag{1}$$

where the coefficients A_{ij} are in units of radians. The linear range of the S-curve is 10 to 14 μm, according to commercial specification. The following steps are used to design the DOE and obtain each coefficient A_{ij}. First, the relative distance between the disk and the objective lens is set to be 400 μm. Under this condition and the specification shown in Fig. 1(b), the position of the astigmatic focus-error detector can be determined and the current A_{ij} is 0. Second, because half of the maximum linear range of the S-curve is 7 μm, the relative distance between the disk and the objective lens is then set to be 393 μm. The coefficient A_{ij} is optimized to have the returned beam from the disk passing through the DOE and focusing in one direction on the astigmatic focus-error detector. In this step, the A_{ij} in the direction, such as $A(y)$ in the y direction, can be determined. Third, the relative distance between the disk and the objective lens is then enlarged to be 407 μm. Using the same method, A_{ij} in a direction such as $A(x)$ in the x direction, can be determined. Therefore, the phase polynomial is

$$\phi=A_{20}(x/r_x)^2+A_{02}(y/r_y)^2, \tag{2}$$

where r_x and r_y are the radius of the DOE in x and y directions, respectively, and $A_{20}x^2$ *and* $A_{02}y^2$ serve as the combination of a focusing lens and a cylindrical lens that converges the beam and generates the astigmatism. Many sets of parameters can provide the solutions to Eq. (2). Considering the feasibility of micromachining, the minimum linewidth of the DOE pattern has to be larger than 2 μm. The ZEMAX simulated S-curve matching these requirements is shown in Fig. 5.

The linear range of the focus error signal (S-curve) is 11 μm, which is comparable with that of current commercial optical pickups. The linear range is from 394 to 405 μm. But the best focus distance is shifted from the middle value of 399.5 μm to 398 μm. This is the inherent limit of micro-optical pickups, since the distance between the disk and the photodetector is small. With the advantage of using DOEs, a passive assembly can also be utilized for adjusting the relative distance of the photodetector and DOE, as described in Ref. 7.

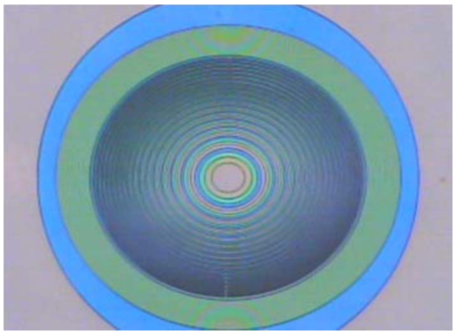

Fig. 6 Photograph of the four-phase leveled DOE.

4 Experimental Results

To demonstrate the function of the DOE, its pattern was etched on a SiN layer of a silicon wafer by standard lithography processes. It was designed to be a four-phase leveled DOE considering the limit of our etching tool. Two steps of etching was utilized to realize it. Each DOE etching depth were therefore optimized to be around 148 nm for the SiN refractive index=2.1. The alignment error between the two etching steps was controlled to be within $\pm 0.25\ \mu$m. After etching the SiN pattern on the front side of the silicon wafer, a teflon-made tool was used to protect the front side with a SiN pattern. The back side of the wafer was then bulk-etched until etching stopped at the front SiN film. Figure 6 shows the captured image of a suspended SiN-based DOE under a microscope. To measure its optical performance, a setup illustrated as Fig. 7 was used. The wavelength of laser is 650 nm. Lens 1, pinhole, and lens 2 are used to provide the convergent beam, of which the convergence is equivalent to the case in the designed micropickup. Since the resolution of the image is over the limit of the charge-coupled device (CCD), a 10× image expander is added. The measurement images are shown in Figs. 8(a)–8(e). Each image is equivalent to the case of the distance between the objective lens and the disk being 394 μm [Fig. 8(a)], 396 μm [Fig. 8(b)], 398.5 μm [Fig. 8(c)], 402 μm [Fig. 8(d)], and 405 μm [Fig. 8(e)]. We also measured the diffraction efficiency, which was about 68% and lower than the theoretical value of 81%. The difference can be attributed to the misalignment between the two etching steps, the error of etching depth, and the absorption and roughness of the SiN layer. Although the measured value is not high, the image of the spot is normally distributed and no severe aberration appears.

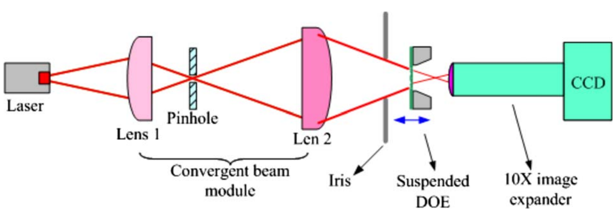

Fig. 7 Schematic illustration of the optical measurement system for the four-phase leveled DOE.

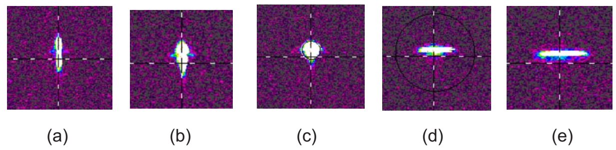

Fig. 8 Measured images from the suspended four-phase leveled DOE.

5 Conclusion

A micropickup design for small form factor optical drives is presented. Among the optical elements, the function, design procedure, and fabrication of the key element DOE is proposed. By using a DOE assisted by a 45-deg upward beamsplitter, the optical configuration is efficiently simplified without sacrificing much efficiency. The number of components is also reduced. The experimental result of the DOE is satisfactory with a spot image approaching the simulation. An embodied system based on this feasible design concept will be implemented hereafter. Furthermore, we hope that this design has the potential to be applied to a portable storage system of small form factor in the future.

Acknowledgments

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