층 밀리 간섭계를 이용한 고체침지렌즈의 광학적 성능 평가

Optical Performance Evaluation of SIL Assembly with Lateral Shearing Interferometer

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Abstract

There has been studied how to minimize the spot size to increase data capacity. Optical data storage devices are being developed near practical limits with wavelength and NA of 405nm and 0.85. There has been studied many types of next generation storage devices such as blu-ray multilayer system, probe based data storage and holographic data storage. Among these data storage devices, solid immersion lens (SIL) based near field recording (NFR) has been widely studied. In this system, SIL is the key component that focuses the laser beam with a very small size which enables ultra high data capacity. Therefore, optical performance evaluation system is required for SIL assembly. In this dissertation, a simple and accurate SIL assembly measurement method is proposed with wedge plate lateral shearing interferometer (LSI). Wedge plate LSI is cheaper than commercialized interferometer, robust to the vibration and the moving distance for phase shifting is large that is order of micrometer. We designed the thickness, wedge angle, material, surface quality and wavelength of wedge plate as 1mm, 0.02degree, fused silica, lamda/10 (10-5) and 405nm, respectively. Also, we confirmed simulation and experimental results with quantitative analysis. This simple wedge plate LSI can be applied to different types of SIL such as solid immersion mirror (SIM), hemispherical, super-hemispherical and elliptical SIL.

Key Words : Wedge plate, lateral shearing interferometer, SIL, optical performance evaluation, near-field recording

1. Introduction

As a leading technology on high density optical storage device, solid immersion lens (SIL) based near-field recording (NFR) has been widely studied. To achieve a high numerical aperture (NA) with a SIL assembly, the beam from laser diode should be focused exactly on the SIL bottom surface through an objective lens. Therefore, the accurate distance between objective lens and the SIL is the most considerable factor on SIL assembly. Up to now, an expansive commercialized interferometer is used for optical performance evaluation. In this study, we developed an evaluation method of SIL assembly with lateral shearing interferometer (LSI) which is insensitive to the vibration and doesn't need a reference beam [1]. Also experimental result is compared to simulation result.

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2. Solid Immersion Lens System

Solid immersion lens (SIL) is the key component in near field optical recording system. And the main role of SIL is reducing the spot size with high NA which is over 1. The spot size is expressed as following equation.

$$FW_{\frac{1}{e^2}} = s \square \frac{\lambda}{NA} \tag{1}$$

where FW, s, λ and NA represent full width, spot size, wavelength and numerical aperture, respectively. As shown in the Eq 1 spot size can be reduced by shorter wavelength and large NA. Many kinds of SIL such as hemispherical, super-hemispherical and elliptical SIL were introduced to get a high NA. Among these different types of SIL, super-hemispherical SIL is widely studied and manufactured. In super-hemispherical SIL, the light from laser diode is focused at the aplanatic position of super-hemisphere where spherical aberration and astigmatism are zero. It is expressed by

$$t = r(1+\frac{1}{n_{SIL}}) \quad (2)$$

where t and r represent total length from surface to aplanatic position and radius of SIL, respectively [2]. Fig. 1 shows the schematic diagram of super-hemispheric SIL. In this system the incident beam refracts by objective lens and SIL. The incident angle in super-hemispherical SIL is higher than that of hemispherical SIL which yields higher NA. Relations for aplanatic position and spot size of super-hemispherical SIL are calculated as follows.

$$\sin\theta'_m = n_{SIL}\sin\theta_m \quad (3)$$

$$s' = \frac{\lambda}{NA} = \frac{\lambda}{n_{SIL}\sin\theta'_m} = \frac{\lambda}{n^2_{SIL}\sin\theta_m} \quad (4)$$

With this equation we confirmed that the spot size of super-hemispherical SIL reduced by n^2_{SIL}. Therefore, we can get much smaller spot with high NA that yields high data capacity.

3. Solid Immersion Lens Design and Tolerance Analysis

3.1 Design of Solid Immersion Lens

Prior to do an optical performance evaluation of SIL

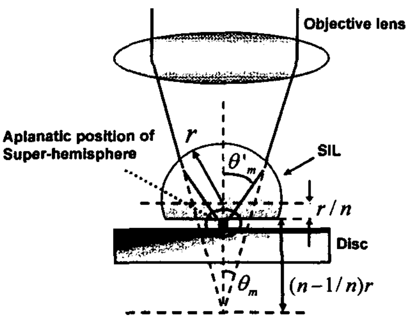

Fig. 1 Wedge plate lateral shearing interferometer

assembly, we are going to verify what the sensitive factors are. The optical path of optimized SIL assembly is shown in Fig. 2. The collimated beam is refracted by an objective lens, NA of 0.42, effective focal length of 2.97mm and entrance pupil diameter of 2.4mm. The beam focusing at an aplanatic position of super-hemisphere whose wavefront error is zero. The design specification of SIL and SIL assembly are noted in Table 1.

3.2 Tolerance Evaluation of Solid Immersion Lens

When the optics is designed, it is important to check the manufacturing possibility of the optics. Therefore, tolerance evaluation is important. With the designed SIL, we perform the tolerance evaluation of SIL. We evaluate tilt and decenter tolerance of SIL, decenter tolerance of SIL assembly and the distance tolerance between objective lens and SIL. We simulate tilt and decenter as increase the tilt angle and move in a certain distance. Wavefront error below 0.035λ is permissible for manufacturing. Tolerance evaluation of tilt and decenter of SIL and decenter and distance tolerance of SIL assembly is presented in Table 2. Through this tolerance evaluation, the distance between objective lens and SIL is the most sensitive as 1.05μm. Therefore, an accurate measurement for rapid change of optical performance is required.

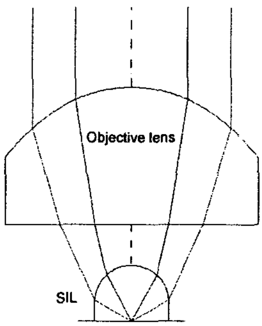

Fig. 2 Optical path of optimized SIL assembly

Table 1 Specification of designed SIL

Wavelength		405nm
Effective NA		1.81
Effective Focal Length		1.43mm
Entrance Pupil Diameter		2.4mm
SIL	Diameter	0.8674mm
	Material	LAH79
	Refractive Index	2.0749

Table 2 Tolerance evaluation of SIL assembly

Contents		Tolerance (below 0.035wv)
SIL	Tilt	1.2°
	Decenter	25mm
SIL assembly	Decenter	24mm
	Decenter	1.05μm

4. Current SIL Measurement Method

4.1 Twyman-Green Interferometry

As an optical performance evaluation system of SIL, Twyman-Green interferometer is widely used. Fig. 3 shows the Twyman-Green Interferometry setup for optical performance evaluation of SIL assembly. The reference beam reflects from reference mirror interferes with the beam which reflected from SIL assembly. In this interferometry setup, the optical path between the reference mirror to the center of beam splitter and bottom surface of SIL to the center of cubic beam splitter should be the same for good interferogram. In this evaluation setup, there exist many weak points. The interferometer is not only expensive to buy but also difficult to setup precisely. The optical performance of all optical components which consist of the interferometer should be good. And also, it needs very accurate translator such as nano-stage for phase shifting. Furthermore, the scratch can be introduced when we check asymmetric aberration such as astigmatism and coma by moving the grating close to the bottom of SIL surface.

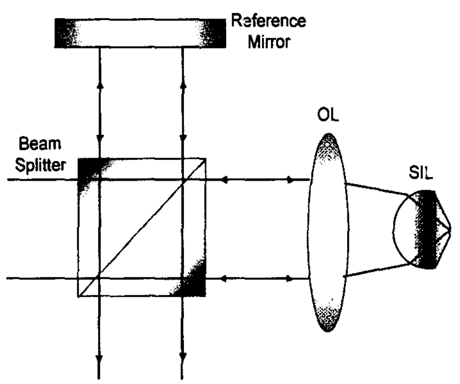

Fig. 3 Twyman-Green interferometer for SIL measurement

4.2 Twyman-Green Interferometry

In this experiment we use collimated laser whose wavefront error is 0.051λrms as a light source, 5:5 cubic beam splitter which is anti-reflection coated at 405nm and reference mirror whose surface figure of λ/20 at 633nm. We did simulation with commercialized calculation program: Matlab for check the interference pattern prior to experiment. Fig. 5 shows the results of simulation and experiment for x and y direction tilt. Discontinuous interferogram is introduced in the boundary of far-field and near-field region. Due to the phase difference, the dark and bright fringes between far-field and near-field region are shifted at amount of π. There introduces less phase discontinuity in y-direction tilt than x-direction tilt. Astigmatism and field curvature were the biggest aberrations with 1.1923λ and -0.4680λ from the simulation results. With the quantitative analysis the phenomenon meets well in both direction tilt.

5. Suggested Wedge Plate Lateral Shearing Interferometer

5.1 Review of Wedge Plate LSI

With a wedge plate, the optical performance is simply and accurately evaluated. Large moving distance that is order of micrometer for phase shifting yields accurate measurement. The reference beam is unnecessary because the incident beam splits itself into two by the wedge plate. Therefore, SIL assembly can be measured simply and accurately.

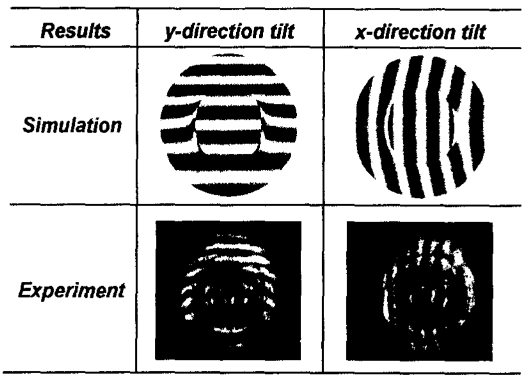

Fig. 4 Results of simulation and experiment with Twyman-Green interferometer

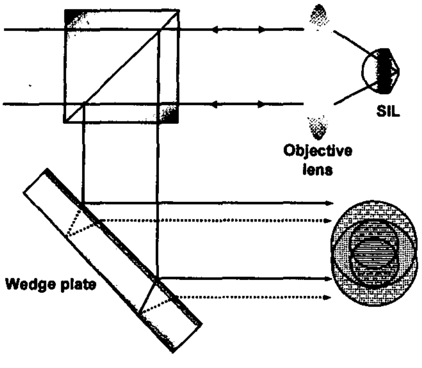

Fig. 5 Suggested wedge plate lateral shearing interferometer

With these reasons, wedge plate lateral shearing interferometer (LSI) which is shown in Fig. 5 is a good method for SIL measurement. Due to the thickness of wedge plate, the original beam reflected at the front surface and the sheared beam reflected at the back surface sheared at a certain distance. Design considerations for wedge plate are presented as follows.

5.2 Wedge Plate Design

There are four consideration factors for wedge plate design that are shearing distance, coating, the number of fringe and phase shifting method. First of all, shearing distance can be obtained in a relation with wavelength, thickness, refractive index and incident angle of wedge plate. Secondly, coating specification is decided with wavelength and incident angle, reflectance and transmittance of first and second surface of wedge late. Then, the number of fringe is calculated with wedge angle, wavelength, refractive index of wedge plate and Snell's law. Finally, phase shifting method can be decided with wavelength, wedge angle, refractive index and incident angle.

5.2.1 Shearing Distance

In a wedge plate LSI, the lateral shear S between the original wavefront and the sheared wavefront is expressed as follows [2],

$$S = \frac{h \sin 2\theta}{(n^2 - \sin^2\theta)^{1/2}} \quad (5)$$

where S, h, n and θ are the shear distance, plate's thickness, refractive index and incident angle, respectively. The shearing distance increases as the plate's thickness increases and refractive index decreases. As $\sin\theta$ is sinusoidal function, shear distance is changed as incident angle increases or decreases. Fig. 6 shows the schematic diagram of wedge plate. The specifications of wedge plate are noted in Table 3. According to the plate's thickness, refractive index and incident angle, the sheared beam reflected from the back surface is calculated as 0.77mm.

5.2.2 Coating

In a wedge plate lateral shearing interferometer, coating is an important factor to get a sharp fringe. The intensity of original wavefront reflected front surface and sheared wavefront reflected back surface of wedge plate should be the same for good fringe visibility. When it coated, there is no way to correct the multi-layers on each side of wedge plate. Therefore, we should perform an accurate coating design. To get a similar intensity between original wavefront and sheared wavefront at the exit plane, suitable reflectance of surface 1 and 2 is needed. To remove second or third reflection from the back surface of wedge plate, we designed dielectric coating in both surface of wedge plate. Table 4 shows the optical coating design specification of each surface. According to the reflectance of first surface as 20% and second surface as 31%, the final intensity at the exit pupil plane is 20% and 19.84%, respectively.

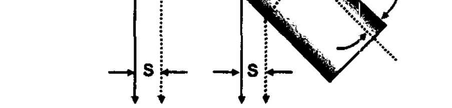

Fig. 6 Schematic diagram of wedge plate

Table 3 Design specification of wedge plate

Wavelength	405nm
Diameter	6mm (clear aperture 5mm)
Thickness	1mm (±0.1mm)
Wedge angle	0.02° (±30sec)
Surface flatness	λ/10 , 10-5
Material	Fused silica (n=1.47 at 405nm)

Table 4 Optical coating design specification of wedge plate

Surface	Layer	Material	Refractive Index	Optical Thickness (λ_0=405nm)	Physical Thickness (nm)
S1	Medium	Air	1.00000		
	1	SiO_2	1.47354	0.1	25.31
	2	HfO_2	2.05827	0.25	45.31
	Substrate	UV	1.48500		
	Total			0.35	70.62
S2	Medium	Air	1.00000		
	1	SiO_2	1.47267	0.2	51.61
	m	HfO_2	2.05433	0.25	46.24
	3	SiO_2	1.47267	0.25	64.51
	4	HfO_2	2.05433	0.25	46.24
	Substrate	UV	1.48500	0.95	
	Total			0.95	208.60

5.2.3 The Number of Fringe

In a wedge plate LSI the wedge plate introduces tilt to the sheared wavefront. Therefore, it is important to decide how many fringes we want to see. It is strongly concerned with the wedge angle of wedge plate. Fig. 7 shows reflect and refraction angles in a wedge plate. Let's put incident angle, wedge angle and refractive index of wedge plate as θ_1, α and n. Then, the angle of reflection from the first surface would be the same as incident angle of θ_1. According to the Snell's law, the refraction angle of θ_2 in the first surface expressed as follows.

$$\theta_2 = \sin^{-1}(\frac{\sin\theta_1}{n}) \tag{6}$$

The beam refracts from the first surface enters to the second surface with an angle of θ_2. Due to the wedge angle, the incident angle at the second surface changes as $\theta_2 + \alpha$. Therefore, the incident angle at the first surface which reflected from the second surface would be expressed as $\theta_2 + \alpha + \alpha$. Finally, the angle of sheared beam θ_3 can be expressed as

$$\theta_3 = \sin^{-1}(n \sin\theta_2 + 2\alpha) \tag{7}$$

Therefore, the difference between the angle of reflected original beam and the refraction angle of sheared beam is expressed as follows,

$$\theta_d = \theta_3 - \theta_1 \tag{8}$$

where θ_d represents difference between θ_1 and θ_3.

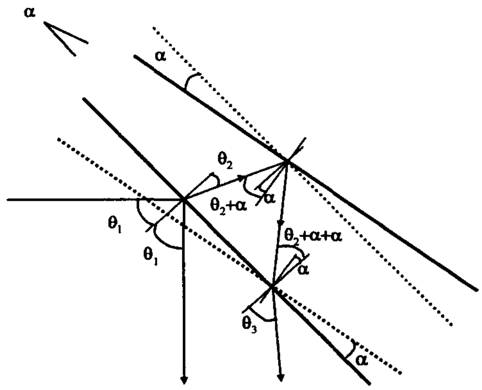

Fig. 7 Reflect and refraction angles on each surface

Therefore, the fringe separation from the wedge plate can be expressed as

$$\Delta y = \frac{\lambda}{\sin\theta_d} \tag{9}$$

Let's apply these equations for our wedge plate whose wedge angle and refractive index of 0.02° and 1.47. In case of the incident angle of 45°, refraction angle of θ_2, θ_3 and difference of these two angle of θ_d would be 28.752°, 45.073° and 0.0073°, respectively. When we put wavelength as 0.000405mm, the fringe separation will be 0.318mm. Therefore, around 7 bright fringes will be shown in the exit diameter of 2.4mm. Furthermore, 5 bright fringes will be shown in an overlapped shearing area of 1.63mm.

5.3 Simulation and Experimental Results

Prior to perform a wedge plate LSI, we examined the phenomenon of lateral shearing interferometer with some optical components such as beam splitter and mirror. When we first look at the phase of sheared area that is shown in Fig. 8 there introduces more than π in the boundary of far-field and near-field region. Fig. 9.a shows an experimental setup with two beam splitter and one right angle prism. When the beam enters the first beam splitter, one goes right and the other goes straight and reflects with a right angle prism. The optical path of two beams should be proportional to the integer. In this experimental setup we rotate the right angle prism to get sheared interferogram. Fig. 9.b shows a different experimental setup with one beam splitter and two mirrors. This setup is somewhat similar with Twyman-Green philosophy. In this experimental setup, one mirror adjustment yields sheared interferogram. Fig. 10 shows the simulation and experimental results with a different shear ration. According to the two results, we confirmed that the simulation and experimental results are well matched in a quantitative analysis. Because the two beams interfere by themselves with similar phase, there is no fringe discontinuity as in the result of Twyman-Green interferometer.

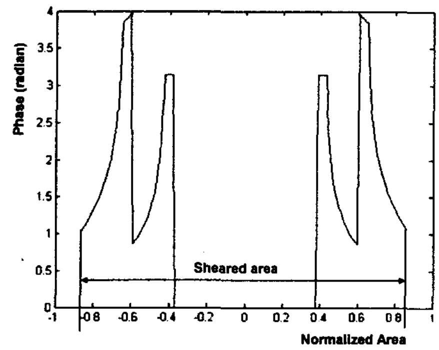

Fig. 8 Phase of sheared area

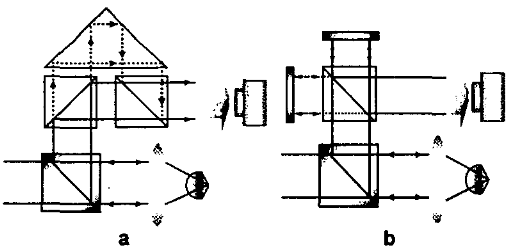

Fig. 9 Experimental setup

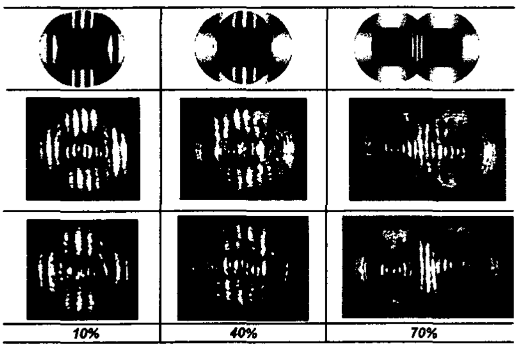

Fig. 10 Simulation and experimental results

6. Conclusions

In this study, we developed a SIL assembly evaluation method with lateral shearing interferometer. Lateral shearing interferometer is simple and accurate method for optical performance evaluation on SIL assembly with less effort than Twyman-Green interferometer. And it can be applied to different types of SIL that is hemispherical, Elliptic SIL and solid immersion mirror (SIM).

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Reference

[1] F. Zijp, J. M. A. van den Eerenbeemd, P. Urbach and C. A. Verschuren, 2006, "Effects of Polarization on Wave Front Measurements and Manufacturing of Solid Immersion Lenses for Near-Field Optical Recording", Jpn. J. Appl. Phys. 45 , 1341.

[2] Max Born and Wolf, 1980, Principle of Optics, Seventh Edition Pergamon, Oxford, Chater 7.5

[3] Jae Bong Song, et all, 2004, "Simple phase-shifting method in a wedge-plate lateral shearing interferometer", Appl. Opt. 43, 3989-3992.

[4] Daniel Malacara, 1992, Optical Shop Testing, John Wiley & Sons, Chapter 4.

[5] Daniel Malacara, Manuel Servin and Zacarias Malacara, 2005, Interferogram Analysis for Optical Testing, Taylor & Francis, Chapter 1.

[6] M.V.R.K Murty, 1964,"The use of a single plaen parallel plate as a lateral shearing interferometer with a visible gas laser source", Appl. Opt. 3, 531-534.

[7] H.-H. Lee, J.-H. You, and S.-H. Park, 2001, "Phase-shifting lateral shearing interferometer with two pairs of wedge plates," Opt. Lett. 26, 140-141.

[8] G. Harbers, P. J. Kunst, and G. W. R. Leibbrandt, 1996, "Analysis of lateral shearing interferograms by use of Zernike polynomials," Appl. Opt. 35, 6162-6172.