Optical system and lens design for Blu-ray disc optical pick-up

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During the design process of Blu-ray disc optical pick-up (BD OPU), the optical system and the collimator lens design is especially important. This paper designs an optical system and some lenses for the BD OPU, including collimator lens, beam shaping lens for laser beam shaping, and cylinder lens for signal detecting. In this OPU, we use a triplet lens to collimate the laser beam. At the same time, we build a series of assembly jigs to make sure that each lens can be put into the OPU basement properly. At last, we get the reading spot image and S-curve photo of OPU, which can be used to read Blu-ray disc (BD).

OCIS codes: 210.0210, 220.0220, 230.0230.

In the global market of the optical data storage, CD, CD-ROM, DVD-ROM, DVD-RW, DVD+RW and so on are widely used. Although compared with CD, current DVD already has considerable progress in storage density and read-write speed, the enhanced step is still restricted by the red laser, which spurs the requirement of new generation of blu-ray technology. The new technology uses the blue ray laser wave band to carry on the work, and the storage capacity may increase nearly 5 times or more, causing a technological breakthrough of high density of optical data storage[1−3]. Table 1 introduces the format for Blu-ray disc (BD) with single layer.

In this paper, according to the format for BD with single layer, we build up a commercial optical system for the Blu-ray disc optical pick-up (BD OPU) and the ray-path with optical elements is shown in Fig. 1.

As the selected laser diode (LD) does not have the feedback function, we need to build a special optical part for LD power control. Therefore, BD OPU optical system should be composed of the following three partial optical ray paths: collimating, beam shaping and laser power controlling. Table 2 gives the basic parameters of SONY LD whose grade is SLD3233VF-53[4].

Table 1. Format for BD with Single Layer

Capacity	23.3/25/27 GB (Single Layer)
Wavelength of the Laser	405 nm
NA of the Objective Lens	0.85
Data Transfer Rate	36 Mbps
Diameter of the Disc	120 mm
Thickness of the Disc	1.2 mm
Diameter of the Center Hole	15 mm
Recording Method	Phase Change
Signal Modulation	1 − 7PP
Data Track	Groove Recording
Addressing Method	Wobble
Visual Data	MPEG-2 Video
Audio Data	AC3, MPEG-1, Layer2, Others
AV Multiplex Method	MPEG-2 Transport Stream

From Table 2, the parallel and perpendicular radiation angles can be obtained. These decide the numerical aperture (NA) of collimator lens.

In the collimation path of rays, we mainly designed the triplet lens to avoid using asphere lens, because the cost of asphere lens is much higher than triplet lens with the same performance. In the asphere lens market, although there are many types of ready-made products, special lens for our LD is few and not suitable for this system. Therefore we designed the collimator lens according to the theoretically requirements for the LD radiation angle and objective lens.

In BD OPU system, the basic requirement for objective lens which is written in Blu-ray disc read-only format[5] is that NA should be 0.85. The first objective lens with a NA of 0.8 was developed using a two-element lens to increase the fabrication tolerance in 1997[6]. Then in order to correct chromatic aberration caused by mode hopping and wavelength change of the laser diode, a three-element objective lens with NA of 0.85 at 405 nm was proposed in 2002[7]. Almost at the same time, the first single objective lens that has the NA of 0.85 was developed in Victor Company of Japan, Ltd. (JVC)[8]. Then in 2003, JVC published the design principle for single

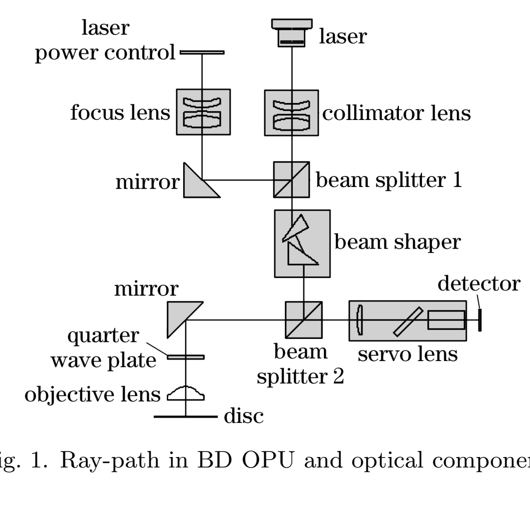

Fig. 1. Ray-path in BD OPU and optical components.

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Table 2. Parameters of the Sony Laser (SLD3233VF-53) (Electrical and Optical Characteristics $T_c = 25$ °C)

Item		Symbol	Conditions	Min.	Type	Max.
Threshold Current (mA)		I_{th}	CW	–	35	65
Operating Current (mA)		I_{op}	CW, $P_0 = 65$ mW	–	80	110
Operating Voltage (V)		V_{op}	CW, $P_0 = 65$ mW	–	5.3	6.5
Wavelength* (nm)		λ_p	CW, $P_0 = 65$ mW	400	405	410
Differential Efficiency (mW/mA)		η^D	CW, 5 – 65 mW	0.9	1.4	–
Radiation Angle	Parallel * (deg.)	$\theta_{/\!/}$	CW, $P_0 = 65$ mW	6.5	8.5	11
	Perpendicular* (deg.)	$\theta_\perp$		18	21	24
Astigmatism (μm)		A_s	CW, $P_0 = 65$ mW	−6	–	0
Positional Accuracy	Angle* (deg.)	$\Delta\phi_{/\!/}$	CW, $P_0 = 65$ mW	–	–	±2.0
		$\Delta\phi_\perp$		–	–	±2.5
	Position (μm)	$\Delta x, \Delta y, \Delta z$		–	–	±80

*Inspection standard.

objective lens with NA of 0.85[9]. Although at that time this single lens is difficult to be produced, it makes lower cost possible. When the technology was developed, single lens cost less than the two- or three-element lens. In 2004, Matsushita Electric Industrial Co., Ltd. developed the compatible objective lens for BD and digital versatile disk (DVD)[10,11]. In 2005, Konica Minolta Co., Ltd. produced the plastic objective lenses for BD OPU[12]. Till that time, the objective lens had been successfully developed from research to product. In this paper, we choose the objective lens produced by Konica Minolta Co., Ltd. for BD OPU whose type is T963[13]. The detail data of the objective lens is supplied by Philips Investment Co., Ltd. Shanghai R and D Centre[14].

In the proposed Blu-ray optical system, the objective lens's parameters are shown in Table 3. This objective lens is a glass singlet (glass molded or glass replica). It will be used in a BD OPU, which is designed for single lens DVD compatibility by means of a separate optical component[14].

The spot size is calculated according to the Airy disk[15]

$$R = 0.61\lambda/\mathrm{NA}, \tag{1}$$

where R is the spot radius and λ is the wavelength. However, we usually use Eq. (2) to calculate the spot size:

$$R = 0.77\lambda/\mathrm{NA}. \tag{2}$$

We may obtain the Airy disk radius of the objective lens:

$$R = 369.6 \text{ nm}. \tag{3}$$

According to Table 2, we may obtain the laser horizontal divergence angle which is 8.5° and the vertical divergence angle which is 21°. So, we can calculate the focal length of collimator lens:

$$f_{\mathrm{CL}} = D/2/\mathrm{tg}(\theta_\perp/2) = 10.791, \tag{4}$$

Table 3. Parameters of the Objective Lens

Focus Length (EFL)	2.35 ± 0.05 mm
Numerical Aperture (NA)	0.85 ± 0.01
Enter Pupil Aperture (D)	4.0 mm

where D is the enter pupil aperture. The NA of collimator lens is

$$\mathrm{NA}_{\mathrm{CL}} = \mathrm{tg}(\theta_\perp/2) = \mathrm{tg}(21/2) = 0.185. \tag{5}$$

Therefore we may obtain the Airy disk radius R_{CL} of collimator lens:

$$R_{\mathrm{CL}} = 0.77\lambda/\mathrm{NA} = 1698.2 \text{ nm}. \tag{6}$$

According to the above theory and computation, we designed the triplet lens, and the parameters of the triplet lens are shown in Table 4.

Finally, we get the layout and the spot diagram of the collimator lens as Figs. 2 and 3 show. From Fig. 3, when field angle is zero degree and in the ideal condition, the spot with 0.150 micron root-mean-square (RMS) radius may be obtained. When the field angle is 0.4°, the spot is still very small. So this designed triplet lens is suitable for the requirement of objective lens.

At the same time, we also evaluate the design results by Figs. 4 and 5. Through processing the collimator lens, we obtained the ellipse parallel light with 4-mm vertical direction aperture and 1.6-mm horizontal direction aperture.

We designed the beam shaping ray path, and the principle is shown in Fig. 6. The main purpose is to shape the ellipse parallel light with horizontal direction aperture $D_1 = 1.6$ mm into round parallel light with vertical direction aperture $D_2 = 4$ mm diameter.

The shaping scale M can be calculated by

$$M = \mathrm{tg}(\theta_\perp/2)/tg(\theta_{/\!/}/2) = \cos i_2/\cos i_1, \tag{7}$$

$$M = \mathrm{tg}(\theta_\perp/2)/tg(\theta_{/\!/}/2) = 2.5/1. \tag{8}$$

As we select the glass material K9, its refractive index n_2 is 1.53022, and according to the law of refraction (here $n_1 = 1.0$):

$$n_1 \sin i_1 = n_2 \sin i_2. \tag{9}$$

Table 4. Parameters of the Triplet Lens

	Surf: Type	Radius	Thickness	Glass	Semi-Diameter
OBJ	Standard	Infinity	Infinity		Infinity
ST0	Standard	9.410000	1.660000	BAK7	2.001503
2	Standard	−7.780000	0.600000	ZF6	1.910298
3	Standard	−22.446000	0.500000		1.883660
4	Standard	5.850000	0.900000	BAK7	1.770308
5	Standard	7.164000	7.955139 V		1.608767
6	Standard	Infinity	0.250000	BAK7	0.194649
7	Standard	Infinity	0.500000		0.166244
IMA	Standard	Infinity			0.075271

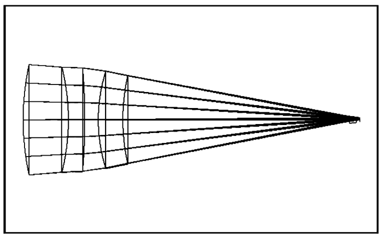

Fig. 2. 3D layout of collimator lens.

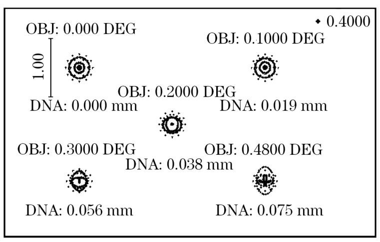

Fig. 3. Spot diagram of collimator lens.

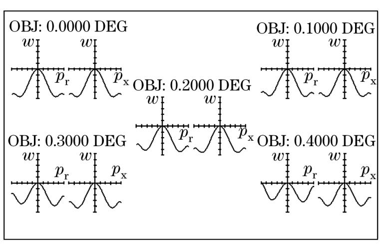

Fig. 4. Optical path difference.

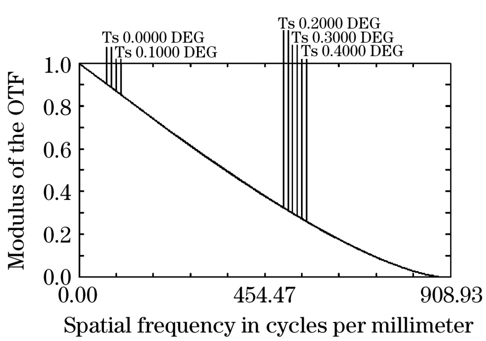

Fig. 5. Polychromatic diffraction MTF.

Associating Eqs. (7)—(9), we got the incidence angle and the beam shaper angle:

$$i_1 = 58.231°, \quad i_2 = 33.7647°. \tag{10}$$

In order to reduce the cost and optical elements manufacture time, we used the fine production-cylindrical lens to make astigmatic aberration for focusing servo method.

As shown in Fig. 7, a cylindrical lens is applied in convergence ray path, so in order to match the cylindrical lens, a convergent lens is set in front of the cylindrical lens. Detail ray path is shown in Fig. 8, and spot diagram through focus on photonic detector integrated circuit (PDIC) as shown in Fig. 9.

Based on the design, we put the LD in the holder and used the planar adjuster to adjust the holder, to make sure the direction of the ellipse beam spot straight, then the gum water was adopted to fix the holder. Then the collimator and u-meter were used to adjust the underside and side of OPU platform parallel the path; We put

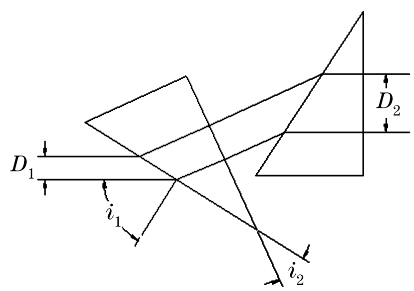

Fig. 6. Shaping path.

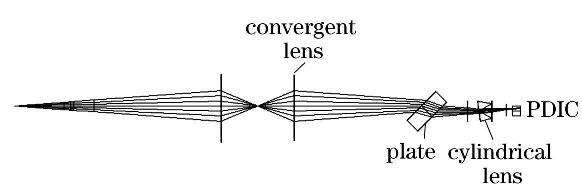

Fig. 7. Cylindrical lens application ray-path.

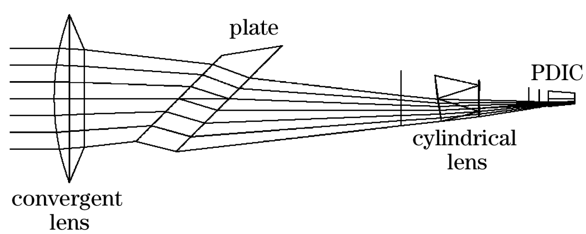

Fig. 8. Detail ray-path.

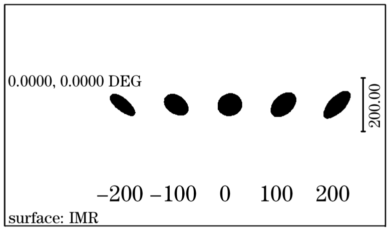

Fig. 9. Spot diagram through focus on PDIC.

the collimator lens in the hole of the holder, and then we could see a beam spot in this receiver. The distance between LD and collimator lens was adjusted until the beam spot did not change when we moved the receiver, which meant we got the parallel beam.

With the help of the angle test instrument, we orderly placed the beam shaping and polarization beam splitter. We could also use the receiver to notarize the beam shaping and polarization beam splitter in the right place.

Then we used the collimator to adjust the mirror. We adjusted the collimator to make the laser light plumb the flat, and a red beam spot was observed in the center of the receiver. Then a mirror was put after turning off the collimator's laser, and adjusting the mirror until we can see a blue beam spot in the center of the receiver. Through adjusting the quarter wave plates, the beam spot was located in the center of the quarter wave plates. We used the collimator to make the objective lens plumb the light until a perfect spot was observed.

Finally, we used a microscope to adjust the cylinder lens. We made an actuator which can hold the objective lens to move up and down, so that we could see the elliptical beam spot to vary to a circular beam spot, and then to an elliptical beam spot again. We revolved the cylinder lens, and then we can get this elliptic beam spot whose direction is about 45°. To stabilize the laser power, photonic detector (PD) board was mounted on the OPU platform and automatic power control (APC) circuits worked properly. We used the planar adjuster to adjust the place of PDIC board until we can get a good S-curve and read-out frequency (RF) signal while searching.

After the assemble process, we got a good spot and S-curve, which shows that this system can be used to read Blu-ray disc. Figure 10, are the photos of the spot coming through the objective lens and cylindrical lens and S-curve photo.

Basically, whether an optical system is good for OPU to read out the signal is judged by:

1) optical parameters including aberrations, spot size and power distribution.

2) focus error signal before closed loop (S-curve).

In Fig. 10(a), the spot size measured by a simple spot analyzer[16,17] is about 270 nm (1/2 of DVD spot size). All the aberrations, especially for coma, were reduced by analyzer at real time. Then in Fig. 10(b), the spot shape on PDIC is consistent with design result at defocusing time. In Fig. 10(c), the S-curve can be used for closed loop as it is symmetric and clear enough. At the same time, we also can see the small pinnacle before the S-curve and it is caused by reflection light of cover glass, and this can be disposed by other servo circuit.

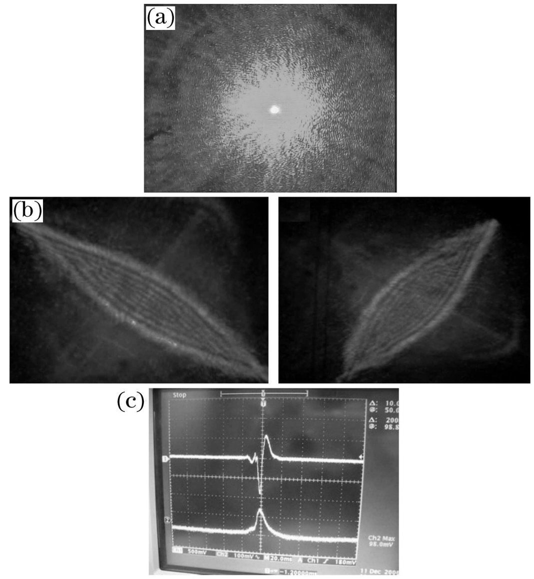

Fig. 10. Spot photos of (a) objective lens, (b) cylindrical lens, and (c) S-curve photo.

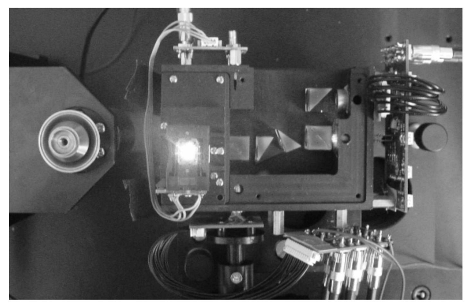

Fig. 11. Photo of BD OPU.

In this paper, we designed an optical system including collimator lens, beam shaping lens and cylindrical lens for BD OPU as shown in Fig. 11. A BD spot by CCD was obtained and compared with the DVD spot. The BD spot is nearly half of the DVD spot. From the S-curve, the results show that it can focus and get the signal on disc.

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