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Abstract. A new optical architecture for holographic data storage system which is compatible with a Blu-ray Disc™ (BD) system is proposed. In the architecture, both signal and reference beams pass through a single objective lens with numerical aperture (NA) 0.85 for realizing angularly multiplexed recording. The geometry of the architecture brings a high affinity with an optical architecture in the BD system because the objective lens can be placed parallel to a holographic medium. Through the comparison of experimental results with theory, the validity of the optical architecture was verified and demonstrated that the conventional objective lens motion technique in the BD system is available for angularly multiplexed recording. The test-bed composed of a blue laser system and an objective lens of the NA 0.85 was designed. The feasibility of its compatibility with BD is examined through the designed test-bed. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.53.2.025102]

1 Introduction

Optical data storage (ODS) systems represented by compact disc (CD), digital versatile disc (DVD), and Blu-ray Disc™ (BD) widely spread taking advantage of their low bit cost for replication of read only disc (ROM) contents compared with magnetic or solid state storage. Their compatibility between recordable media is also found useful for personal archival storage. Recently, the volume of information data surrounding our society is expanding exponentially every year because of tremendous growth in the industry of information technology. In the coming age of the information explosion, the expectations for ODS as an archival storage with a large capacity in addition to reliability, longevity, and low running cost are raised further. A data capacity of optical storage systems has increased step by step due to historical background and has been achieved up to 128 GB/disc by the BDXL™ format. The technological trend of increasing data capacity from CD to BD relies on reducing the size of the diffraction-limited spot by using a laser beam of shorter wavelength and an objective lens of larger numerical aperture (NA). However, the wavelength and the NA in current BD system are already 405 and 0.85 nm, respectively. As long as the same technological trend is simply applied, further improvement of data capacity cannot be expected because material for optical components applicable to ultra-violet wavelength range is lacking, and maximum NA in air is generally limited to be <1.

Holographic data storage system (HDSS) is one of the promising candidates for future ODS system toward achieving a data capacity of over 1 TB/disc. The system can record encoded data page with around a couple of million pixels with a single light pulse. Furthermore, hundreds of data pages can be multiplexed at the same location in the media.[1–4] Considering these features, the HDSS has a high possibility of becoming a post BD system. Up until now, several optical architectures for HDSS have been presented.[5–10] These are classified broadly into three categories as shown in Fig. 1. The optical architecture for angularly multiplexed recording generally has two optical paths for a signal beam and a reference beam with an off-axis optical configuration.[5,6] Regarding the optical architecture for shift multiplexed recording, a reference beam and a signal beam are bundled on the same optical axis and irradiated on a holographic medium through a single objective lens.[7,8] Regarding the optical architecture for micro hologram recording, two counter-propagating signal and reference beams are configured to record bitwise information similar to the BD system.[9,10] Among these architectures, the angularly multiplexed recording demonstrated superior performance of high density recording at 500 Gb/inch².[6]

On the other hand, however, the angularly multiplexed recording tended to be more complicated than other architectures such as shift multiplexed recording or micro hologram recording. Consequently, it had a significant difficulty in taking backward compatibility with the conventional ODS system such as BD. Backward compatibility is necessary for next generation of the ODS system especially in consumer application. One of the factors of the difficulty is due to a lack of affinity with geometry of an optical system of BD. The objective lens in the BD system is placed parallel to a recording medium. In contrast, it is generally inclined with respect to a holographic medium in angularly multiplexed recording to keep a space for reference beam optics.[5,6] The larger NA of the objective lens is introduced for high density recording, the wider diameter of the objective lens is necessary for enough working distance and coping with

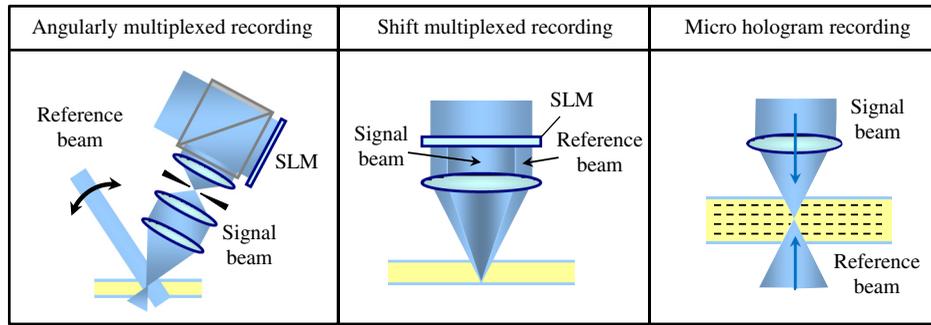*Address all correspondence to: Ken-ichi Shimada, E-mail: kenichi.shimada .ty@hitachi.com

Fig. 1 Representative optical architectures for holographic data storage system.

fast data transfer rate.[11] Thus, an objective lens with NA 0.85 for compatibility was believed to occupy a space in the HDSS with angularly multiplexed recording and was not to be placed parallel to a holographic medium.

In order to overcome the situation in this article, we propose a new optical architecture for angularly multiplexed recording. A single objective lens of NA 0.85 for HDSS, which is shared with BD system, can be placed parallel to a holographic medium, which brings a high affinity with BD system. Through preliminary experiments using a test-bed composed of a green laser system and a low NA objective lens, the feasibility of the new architecture is verified in angularly multiplexed recording. Angular multiplexing can also be realized by moving the objective lens in the same direction as tracking action in conventional BD system. A test-bed composed of a blue-laser system and an objective lens of NA 0.85 is designed to confirm the performance of high density recording and the backward compatibility to BD. Numerical analysis of the wave aberration of the optical path for both HDSS and BD shows highly probable feasibility of the compatibility.

2 Methods

2.1 *Monocular Architecture*

A new concept of optical architecture for HDSS dubbed "monocular architecture" was created in order to realize backward compatibility with BD system. The signal and the reference beams travel through a single objective lens in the new architecture as shown in Fig. 2.[12] The objective lens in the architecture can be placed parallel to the holographic medium. The geometry is the same as that in conventional BD system. The reference beam is focused on the back focal plane of the objective lens by the reference beam lens in the figure. Thus, the reference beam is collimated to a plane wave overlapping with the signal beam in the holographic medium. These two beams interfere with each other and generate interference fringes to be recorded in the medium as a hologram. Since the objective lens works as a Fourier transform lens, the incident angle θ of the reference beam onto the holographic medium is described as Eq. (1),

$$\theta = \sin^{-1}(d/f), \tag{1}$$

where d is a distance between the focal point of reference beam and an optical axis of the objective lens whose focal length is f. Therefore, the incident angle of reference beam can be changed by changing the distance d. Consequently, various signal beams can be recorded at the same position in the medium with the reference beams in their each incident angle as an index of each signal beam. Namely, the angular multiplexing can be accomplished. Figure 3 shows three different ways to change the distance d. It can be changed either by the angle of a reflection mirror just before the reference beam lens [Fig. 3(a)], or by the displacement of the reference beam lens [Fig. 3(b)], or by the
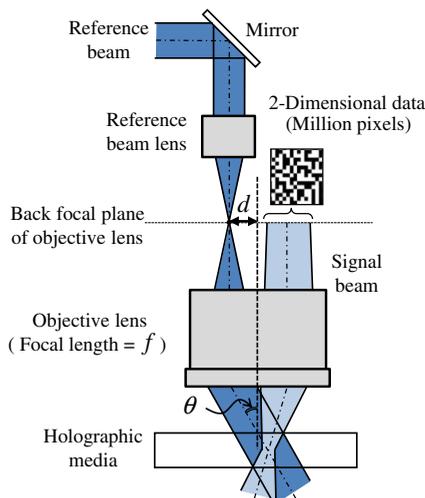
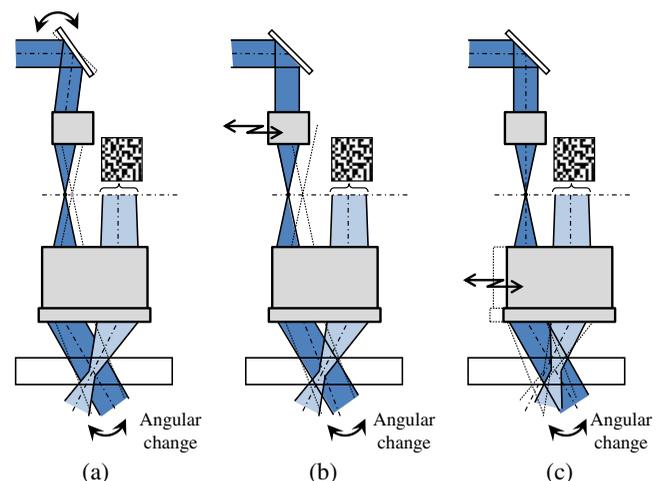

Fig. 2 Overview of monocular architecture.

Fig. 3 Monocular architecture, angular multiplexing by (a) mirror tilt, (b) reference beam lens shift, and (c) objective lens sift.

displacement of the objective lens position [Fig. 3(c)]. In case of the angular multiplexing by the objective lens displacement [Fig. 3(c)], the movement of the lens is identical with conventional BD system. Therefore, it allows making the affinity for BD compatibility higher.

2.2 Compatible Optical System between HDSS and BD using the Monocular Architecture

Light propagation in a compatible optical system between HDSS and BD using the monocular architecture is described schematically in Fig. 4.[13] Figure 4(a) shows light propagation in holographic recording state for both signal and reference beams. A light beam outputted from external cavity laser diode (ECLD)[14] is divided into signal and reference beams by beam splitter (BS). Signal beam is transmitted through the BS proceeds to be incident on a spatial light modulator (SLM). After the amplitude of signal beam is spatially modulated by SLM, the signal beam is focused on a holographic medium by an objective lens of NA 0.85. Reference beam reflected by Mirror1 is focused onto the back focal plane of the objective lens by reference beam lens equipped on an actuator. The focused reference beam is then collimated by the objective, overlapping with the signal beam in the holographic medium. Angular multiplexing is accomplished by changing incident angle of the collimated reference beam with the rotation of Mirror1 or displacement of the objective lens as previously explained in Sec. 2.1 with Fig. 3. On the other hand, Fig. 4(b) shows light propagation during the BD recording/readout state in the common optical system to Fig. 4(a). A light beam emitted from a blue-laser diode is collimated by a collimating lens. The reference beam lens working in Fig. 4(a) is removed and quarter wave plate is inserted in exchange by the actuator from and into the optical path of the collimated beam, respectively. After beam focusing on BD by the objective, the reflected beam travels through the opposite direction along the incident path and is detected by a photo detector. Holographic optical element placed in front of the photo detector that divides the reflected beam into a plurality of beams in order to generate a focusing error signal and a tracking error signal.[15] The monocular architecture will potentially allow making the drive size much smaller and making the affinity for BD compatibility higher than conventional angularly multiplexing architecture because of its unique geometry and its angular multiplexing technique using conventional lens motion in the BD system.

3 Results and Discussion

3.1 Verification of the Validity of the Monocular Architecture

The experimental system for verification of the monocular architecture is shown in Fig. 5. A coherent laser with a power of 100 mW at 532 nm is used as a light source. A phase mask is imaged onto a 1280×1000 data page SLM with a 12-μm pixel pitch using a pair of relay lenses. The mask is moved during angularly multiplexed recording to introduce random phase distribution to the modulated signal beam to mitigate any high frequency enhancement in the recorded holograms.[4] A pair of relay lenses images the SLM to the back focal plane of an objective lens. In between the relay lens pair, a polytopic filter of 5.38-mm square is placed. The size is the square root of 1.2 times larger than Nyquist size on a side. Reference beam is introduced into the objective lens through a reference beam lens to be a plane wave at a medium. The beam size of the plane wave of the reference beam at the medium is ~9.5-mm square that is enough to overlap with signal beam in a holographic medium. The holographic medium is a 1.5-mm thickness InPhase HDS-3000 transparent disk, which is sensitive in the green wavelength range. The objective and reference beam lenses used are the same lenses, which are Hasselblad lenses (*f*#2.0, focal length = 110.8 mm) allowing ~2 deg of sweep range of the reference beam at the angle of 15 deg from the axis of the signal beam. Angularly multiplexed recording is accomplished by shifting either the reference beam lens position (A. in Fig. 5) or the objective lens (B. in Fig. 5). The reproduced signal beams are imaged on a 2200×1726 pixels camera with a 7-μm pixel pitch and detected with an over-sampling detection process.[16] In this experimental system, the holographic medium was forced to be tilted 20 deg to eliminate the directional reflection from the medium and to keep the reflected beam out from the camera because the performance of anti-reflective (AR) coating coated on the surface of HDS-3000 was
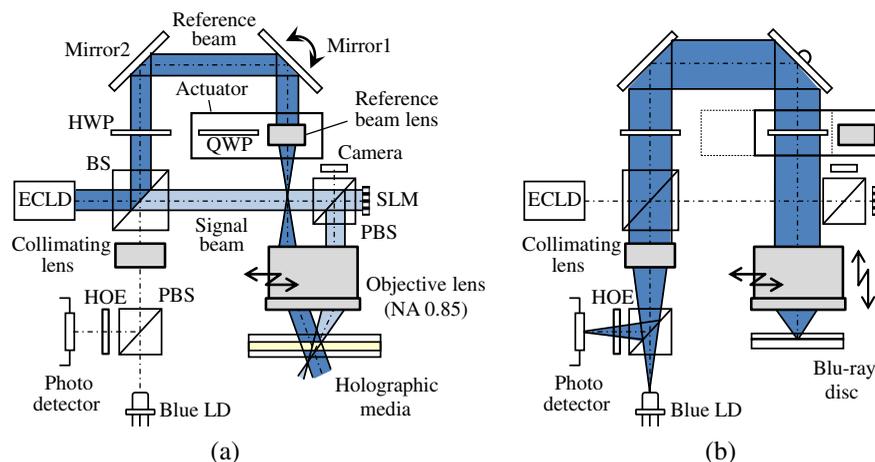

Fig. 4 Optical architecture for backward compatibility with Blu-ray Disc™ (BD) system (a) during holographic recording state and (b) during the BD recording/readout state.
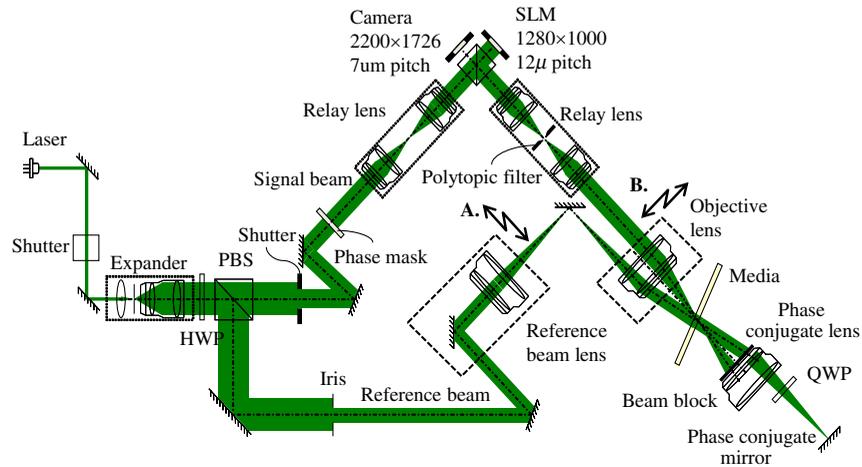
Fig. 5 Monocular experimental setup using green laser system and low numerical aperture (NA) objective lens.

not sufficient. Therefore, the objective lens was not placed parallel to the holographic medium yet in this experiment. However, the tentative configuration is not essential but can be solved by refinement of the coating or still effective to confirm the validity of angular multiplexing in the monocular architecture.

First, an output angle of reference beam with respect to the optical axis of the objective lens was measured in comparison with theory. The solid line and some points in Fig. 6 show theoretical curve expressed as Eq. (1) and measured angles of reference beam within 1 deg resolution of measurement, respectively. Measured angles were in good agreement with theory as expected. Next, Fig. 7 shows the result of a scan of the Bragg angular selectivity curve of the recorded hologram compared to theoretical curve calculated by coupled wave theory.[17] The relationship is theoretically given by Eq. (2),

$$\eta = \sin c^2 \left(\frac{n\pi L}{\lambda} \frac{\sin \theta_{RS}}{\cos \theta_S} \Delta\theta \right),$$ (2)

where η is the normalized diffraction efficiency at Bragg angle, $\Delta\theta$ is the angle off of Bragg, L is the thickness of the recording layer, n is the refractive index of material, λ is the wavelength of the laser, the θ_S is the incident angle
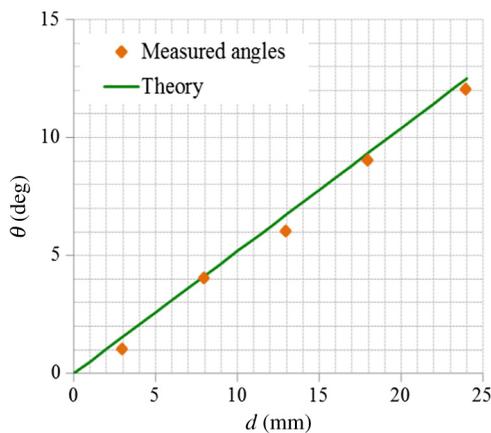
of signal beam inside the medium, and the θ_{RS} is the angle between reference and signal inside the medium. These parameters are summarized in Table 1. The experiment and theory of the Bragg angular selectivity curve also agree well.

Figure 8 shows a graph of SNR of three holograms angularly multiplexed by shifting either the reference beam lens (case A) or the objective lens (case B). The SNR is estimated by Eq. (3),

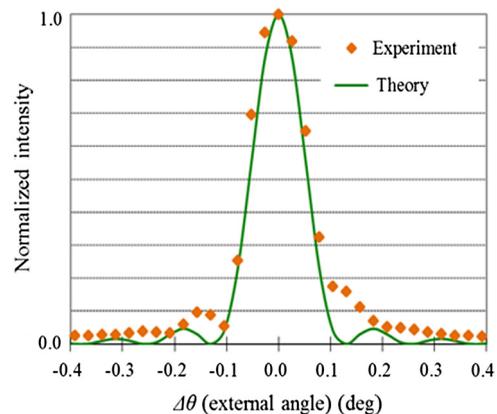$$SNR = 20 \log_{10} \left(\frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \right),$$ (3)

Fig. 7 Bragg angular selectivity curve for single hologram.

Fig. 6 The result of output angle of reference beam with respect to the optical axis of the objective lens.

Table 1 Optical parameters of the experimental system.

Thickness of recording layer	L	1500 μm
Index of refraction	N	1.5
Wavelength	Λ	0.532 μm
Incident angle of signal beam	θ_S	16.7 deg (internal angle)
Angle between reference and signal	θ_{RS}	8.9 deg (internal angle)
Media tilt	Φ	20.0 deg
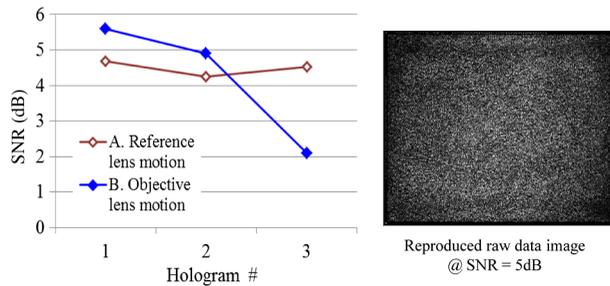
Fig. 8 Measured SNR and reproduced raw data image on camera.

where μ_1 and μ_0 are the mean values and σ_1 and σ_0 are the standard deviations of "1" and "0" of reproduced binary digital signal. The average SNR of both results were 4.6 and 4.2 dB, respectively. There is a strong relationship between this SNR and bit error rate (BER) in our test-bed. Figure 9 is the relationship resulted from using a low density parity check codes[18] with a rate of 0.5, a code length of 16,384 data bits, and fewer than 40 iterations. The BER increases sharply at around 0.5 dB. In this study, we set a criterion of SNR for reproduction at 1.5 dB tentatively. Every obtained the SNR from each hologram exceeds the criterion, although only the third hologram multiplexed by shifting the objective lens has lower SNR than others because a precure was not sufficiently applied to the hologram due to misalignment of a cure beam system in our test-bed.

It was proved that the monocular architecture is capable of angularly multiplexed recording. Though the objective lens could not be placed parallel to the holographic medium yet due to insufficient AR coating of the medium in the experiment, it could be solved and parallel placement must be available with the refinement. We confirm the angular multiplexing both by reference beam lens motion and by objective lens motion. The latter is the identical movement required for an objective lens in the BD system. This can make the affinity for the BD compatibility higher and take advantage of conventional lens motion technique in the BD system. Through these examinations, the validity of the monocular architecture was verified.

3.2 Monocular Architecture Composed of a Blue Laser and an Objective Lens of NA 0.85

To further investigate the performance of the monocular architecture and to demonstrate that the objective lens can be placed parallel to a holographic medium, a test-bed composed of a blue laser system and objective lens of NA 0.85, which are the same as the optical parameters in BD system
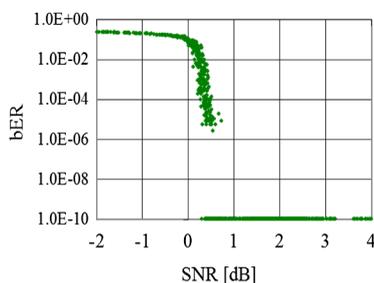

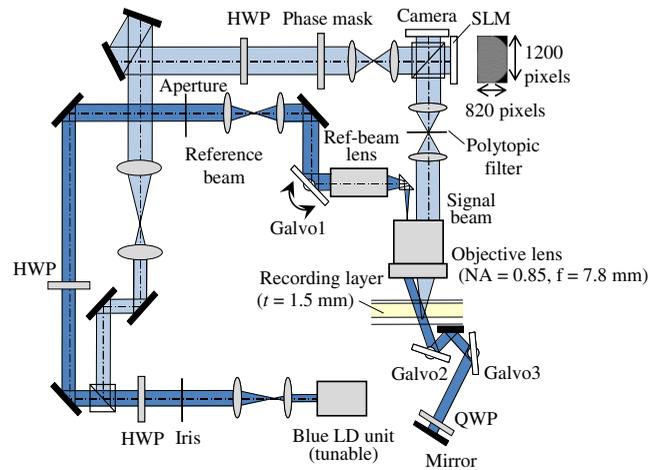**Fig. 9** Relationship between SNR and bit error rate.

Fig. 10 Monocular test-bed composed of a blue laser system and objective lens of NA 0.85.

was designed and fabricated as shown in Fig. 10.[19] The blue laser diode (LD) unit is a modular laser that consists of an ECLD, isolator, and beam expander. The resulting beam is split into a signal and reference beam. The amplitude of the signal beam is spatially modulated using a 1200×820 encoding data page giving a raw data page capacity of 100,676 bytes on an SLM with a 10.7-μm pixel pitch. The objective lens is a custom, high NA lens (NA = 0.85, focal length = 7.8 mm) consisting of six spherical lenses. The objective lens was designed to allow the reference beam to sweep through 30 deg. Both the signal and reference beams pass through the objective lens such that the focal point of the reference beam is at the back focal plane of the lens resulting in a collimated reference beam at the medium. The medium is a custom transparent disk with a 1.5-mm recording layer (photopolymer) sandwiched between a 0.1-mm first substrate and a 1.0-mm second substrate with the AR coating. In the system, phase conjugate readout geometry is used for data recovery. Therefore, two stationary mirrors and two galvano mirrors (Galvo2, Galvo3) are placed on the back side of the medium to retro-reflect the reference beam for data recovery. Recovered holograms are imaged using a 1696×1710 pixel camera with an 8.0-μm pixel pitch and the hologram image is reproduced by over-sampling detection with a ratio of 4:3.

Using this designed test-bed, angularly multiplexed recording was successfully achieved. Figure 11 shows the relative intensity and the SNR of 130 multiplexed holograms recorded by scanning the mirror (Galvo1) angle. Each hologram was offset from the next by an angle of from 0.14 to 0.39 deg over the range. The graph indicates that the quality of 130 multiplexed holograms is sufficient for recovery because the average SNR for all holograms was about 3.2 dB and the BER was under 1.0×10^{-10}. The validity of angular multiplexing using geometry that an objective lens of NA 0.85 is placed parallel to a holographic medium was verified.

3.3 Feasibility Study of Compatibility with Blu-ray Disc™ System

From the viewpoint of wave aberration, preliminary feasibility study of compatibility with the BD system was also examined because wave aberration is a crucial evaluation
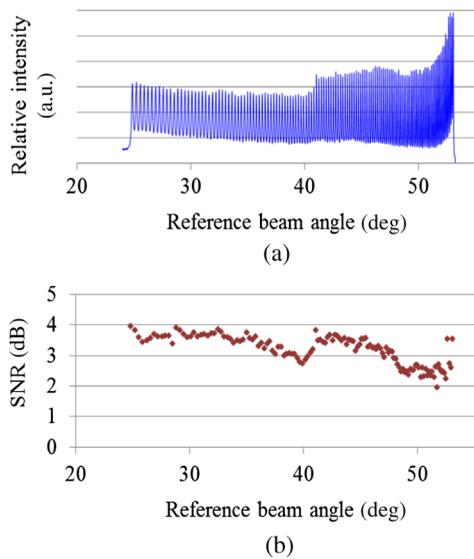
(a)

(b)

Fig. 11 Results of (a) relative intensity and (b) the SNR of 130 multiplexed holograms.

(a)

(b)

WFE = 0.06λ RMS

Fig. 13 (a) Optical model for wave aberration analysis and (b) calculated wavefront.

indicator for both HDSS and BD system. First of all, wave aberration of the optical path for HDSS, whose objective lens is identical with the lens of NA 0.85 shown in Fig. 10, was analyzed. For HDSS using angularly multiplexed recording, the wave aberration of reference beam is critical compared to that of signal beam, and 0.1λ root mean square (RMS) is proposed provisionally as a criterion at previous work.[20] Based on the criterion, wave aberration of reference beam was evaluated. Figure 12 shows wave aberration of reference beam in a holographic medium calculated by ray tracing. In this analysis, the size of the squared aperture for reference beam in Fig. 10 was set so that the reference beam in the medium became 1.5-mm square, which was sufficient to overlap with the signal beam in the holographic medium. Under the condition, it was confirmed that wave aberration could be lower than 0.1λ RMS in overall range of scanning field of 30 deg.

Second, the wave aberration of the optical path for BD system was numerically analyzed. For this analysis, the optical model described in Fig. 4 was utilized where the objective lens is assumed to be identical with the lens of NA 0.85 shown in Fig. 10. With a combination of the objective lens and a collimating lens composed of two aspheric lenses
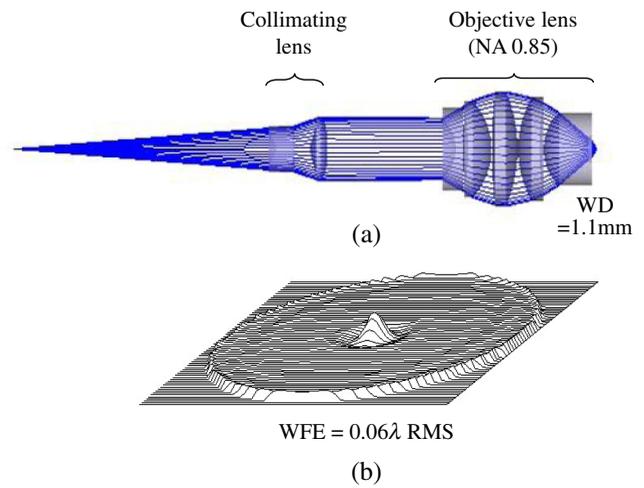
shown in Fig. 13, the on-axis wave aberration of focused beam through a cover glass of 0.1-mm thickness could be reduced to 0.06λ RMS at NA of 0.85. Meanwhile, the working distance between the front edge of the objective lens and the surface of the cover glass could be designed to be 1.1 mm, which is comparable to that of current BD system.[21] Still further improvement of the wave aberration will be required for practical use, but we consider the above result showed highly probable feasibility of the compatibility as a first phase because the wave aberration was at least lower than Marechal criterion of 0.07λ RMS. Only one beam is incident on BD in this system, which means required level of the off-axis wave aberration for the objective lens can be mitigated compared to system employing conventional method such as differential push–pull method, which needs three optical beams with different angles each other incident on the disc for generating a tracking error signal. In this study, from the viewpoint of preliminary analysis, the objective lens was designed to consist of six spherical lenses. If an aspheric lens design technique is employed, the wave aberration in addition to the size of the objective lens could be improved considerably. Through these numerical analyses, the monocular architecture showed a strong possibility to realize compatibility with BD system.
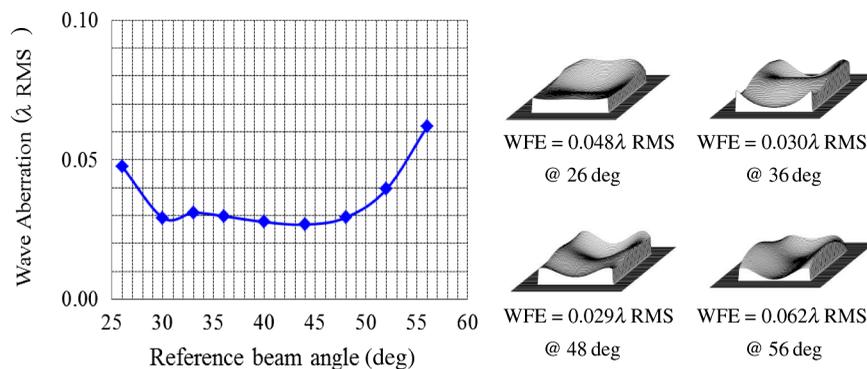

WFE = 0.048λ RMS @ 26 deg

WFE = 0.030λ RMS @ 36 deg

WFE = 0.029λ RMS @ 48 deg

WFE = 0.062λ RMS @ 56 deg

Fig. 12 Wave aberration of various incident angles of reference beam at 26, 36, 48, and 56 deg calculated by ray tracing.

4 Conclusion

New optical architecture called as "monocular architecture" for HDSS using angularly multiplexed recording method compatible with BD system was presented. The new optical architecture allows placing an objective lens with NA 0.85 parallel to a holographic medium and brings a high affinity with the geometry of optical architecture in the BD system. Through the comparison of experimental result of Bragg angular selectivity curve with theory, the monocular architecture was verified and the feasibility of angularly multiplexed recording in it was proved. Angularly multiplexed recording using the lens displacement, which is identical required in an objective lens in BD system, was also demonstrated. This result means that conventional lens motion technique was available for angularly multiplexed recording method. Test-bed composed of a blue laser system and an objective lens of NA 0.85 was designed and feasibility study of the compatibility with BD was examined. Estimated wave aberration met the minimal criterion for both holographic data storage and BD system. The monocular architecture accordingly has a strong possibility to realize compatibility with BD system. In addition to backward compatibility, the new optical architecture will potentially allow making the drive much smaller and simpler than conventional optical architecture based on angularly multiplexing recording method due to its unique geometry.

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Takeshi Shimano received his BS, ME, and PhD degrees from Tokyo Institute of Technology, in 1985, 1987, and 2000, respectively. He developed the optical pickups for optical discs in Central Research Laboratory, Hitachi Ltd. from 1987 to 2007, which partly resulted in his thesis. He is a member of the Japan Society of Applied Physics and an editor of *Optical Review* published by the Optical Society of Japan.

Ken Anderson has BS degrees in engineering physics and computer science from the Colorado School of Mines, an MS degree in electrical engineering, and a PhD degree in optical engineering from the University of Colorado at Boulder. He is currently a cofounder and CEO of Akonia Holographics where he leads a team of engineers in developing holographic data storage as a commercial product.

Kevin Curtis is RealD's Chief Scientist for Illumination Systems. Prior to this he was founder and CTO and eventually CEO of InPhase Technologies, which he spun out of Bell Laboratories. He has authored approximately 50 issued US patents, one book, and more than 100 presentations on optics and lasers. He received his BS, MS, and PhD degrees in electrical engineering from the California Institute of Technology, Pasadena, California.