

Chromatic Correction of High-Performance Solid Immersion Lens Systems

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The chromatic dispersion of hyper-hemisphere solid immersion lens (SIL) systems is discussed. A simple correction mechanism using a diffractive optical element (DOE) is presented that improves the chromatic aberration by a factor of ten.

KEYWORDS: optical data storage, solid immersion lens, aplanatic lens, chromatic aberration, diffractive optical element

1. Introduction

Solid immersion lens (SIL) technology is now being developed as a path to achieve higher data densities on the plane of the recording layer.¹⁾ The SIL lens reduces the effective wavelength of the light illuminating the recording layer, and thus reduces the spot size. Two types of SIL lenses are being developed that use spherical-only surfaces. The first type of SIL lens is a hemisphere with the flat surface in proximity to the recording layer, and the second type of SIL lens is a hyper-hemisphere aplanat with its flat rear surface in proximity to the recording layer. Both systems are shown in Fig. 1. The full-width-at-1/e² spot size for each system is approximately given by $\lambda/\text{NA}_{\text{EFF}}$, where the effective numerical aperture $\text{NA}_{\text{EFF}} = n_{\text{SIL}} \sin \theta_{\text{AIR}}$ for the hemisphere and $\text{NA}_{\text{EFF}} = n_{\text{SIL}}^2 \sin \theta_{\text{AIR}}$ for the hyper-hemisphere aplanat. The minimum spot size for either system is given by λ/n_{SIL} . Since the aplanat has the smallest spot size for a given θ_{AIR} , it is attractive for high density recording. By using a high index material like ZnS or GaP for the SIL, a high-performance SIL system can be obtained where $\text{NA}_{\text{EFF}} \sim 2.0$. However, tolerances associated with the geometrical aberrations of the high-performance SIL system must be considered. In this paper, we discuss chromatic aberration characteristics of the hyper-hemisphere aplanat and a potential correction method.

Figure 2 shows a hyper-hemisphere aplanat used with an objective lens and a diffractive optical element (DOE) that is used to correct chromatic dispersion of the SIL. The thickness of the hyper-hemisphere is t_{SIL} and l is the distance from the front SIL vertex to the virtual object created by the focusing objective lens. The aplanatic condition, which results in a lens that is free of spherical, coma and astigmatism, requires that the following relationships exist for an ideal focusing objective lens:

$$t_{\text{SIL}} = r + r/n_{\text{SIL}}, \quad (1)$$

and

$$l = r + n_{\text{SIL}}r, \quad (2)$$

where r is the radius of the SIL. The ideal focusing objective does not contribute any aberration to the calculation and has a focal length of f_o .

Notice that eqs. (1) and (2) are functions of n_{SIL} , which depends on the wavelength of light. Since the goal of using a SIL in optical recording is to achieve the smallest spot possible, high index SIL materials are used. This is also true in microscopy, where high-NA microscope objective lenses use

SIL-like lenses. However, in microscopy the SIL is usually a lower index material like CaF₂, which is a relatively low index material with unusual dispersive properties. The CaF₂ lens is used in combination with other lenses to correct for the chromatic errors. The maximum numerical aperture (NA) for oil-immersion type microscope objectives is about 1.4.

For optical recording we desire the performance improvement of a high-index SIL and a simple method for correcting chromatic errors. In the following discussion, we investigate a ZnS SIL with $n_{\text{SIL}}(650 \text{ nm}) = 2.34$. We assume that the laser diode wavelength is nominally 650 nm, and the wavelength range is 640 nm to 660 nm. Correction of chromatic errors is accomplished by adjusting the focal length of the DOE.

2. Sample Calculation

A graph of n_{SIL} versus wavelength λ for ZnS is shown in Fig. 3. The value of n_{SIL} is approximately linear in the operating range 640 nm to 660 nm. Figure 4 shows an expanded view of the objective-lens focus area from Fig. 2. The triangles represent the relative chromatic shift in l of a $r = 1.0 \text{ mm}$ SIL and the chromatic focal shift of a real objective lens. Notice that the SIL and the real objective lens have opposite focal shifts with wavelength. The dispersion is the distance between the design wavelength position and the maximum position at the end of the wavelength range. Figure 5 shows the variation of the dispersion of the SIL thickness t_{SIL} and the conjugate distance l . The variation of the conjugate distance l dominates the dispersion. Notice that, as the radius r gets smaller, the amount of dispersion reduces. The dispersion is not a function of the NA.

The dispersion must be corrected in order to operate over a reasonable wavelength range. The consequences of not correcting this type of system can be rather severe. For example, Fig. 6 displays the wavefront aberration of a $r = 1.0 \text{ mm}$ SIL system with $\text{NA}_{\text{EFF}} = 1.875$. Before adding the diffractive optical element (DOE), the peak-to-valley wavefront aberration is greater than 1λ at 660 nm. Our wavelength range of $\pm 10 \text{ nm}$ may be considered large, but variations in laser wavelength occur when the diode changes from read power to write power. These changes may be as large as $\pm 3 \text{ nm}$, which introduces a significant amount of dispersion for large r .

A simple DOE with only weak focusing power is sufficient to correct the majority of the chromatic focus shift caused by the dispersion. Figure 6 also displays the wavefront aberration after correction. Notice that the peak-to-valley wavefront aberration is much less than 0.25λ . Some small amount of spherical aberration is introduced because the SIL is not operating in the exact aplanatic condition after correction, but

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