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Advanced Lens Design for Bit-Wise Volumetric Optical Data Storage

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The storage capacity of a fluorescent bit-wise volumetric optical data storage system is limited by the inter-layer crosstalk and the maximum compensation range of spherical aberration induced by different layers inside the medium. Lens designs of far-field and near-field optical systems suitable for volumetric storage are presented. The maximum compensation range of each design is calculated. The storage densities of far-field and near-field confocal systems in terms of bits-in^{-2} are derived based on the maximum compensation ranges and appropriate data layer spacings that induce a -30 dB maximum level of inter-layer crosstalk. It is shown that an optimized near-field system is able to achieve 1.65 Tb-in^{-2} data density.
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KEYWORDS: near-field optical storage, crosstalk, signal-to-noise ratio, volumetric data storage

1. Introduction

Bit-wise volumetric data storage techniques are attractive candidates to increase data capacity in optical storage devices.[1–7] Configuration of the optical system for this type of recording is similar to conventional disk systems, in that a spinning disk is illuminated by a laser beam that is focused into the disk by an objective lens. Data are recorded and read out as mark patterns in spiral tracks. The objective lens moves on an actuator that responds to servo signals in order to keep the focused beam aligned correctly on the data.[1] A significant difference between conventional recording and bit-wise volumetric recording is that many more layers are accessed in volumetric systems. Especially in fluorescent systems, the number of possible data layers is in the hundreds.[2] As shown in Fig. 1, a laser beam focuses through the substrate to access data layers. In this paper, the potential recording densities of volumetric storage systems are examined based on realistic lens designs.

There are three primary factors that limit capacity in fluorescent volumetric systems. Firstly, the data density in each layer is limited by the spot size formed at the focus of the objective lens. The full-width-at $1/e^2$ of the light spot is approximately $s = \lambda/\mathrm{NA}$, where λ is the laser wavelength and NA is the numerical aperture of the optical system. NA equals $n \sin\theta$, where n is the refractive index in the image space of the lens at the data layers and θ is the marginal ray angle in the image space. The depth of focus of the focused laser beam is $Z_f = \frac{\lambda n}{\mathrm{NA}^2}$. In far-field systems, like the one shown in Fig. 1, the NA is limited to NA $= 1$. The minimal spot size is $s = \lambda$. Near-field techniques using evanescent light, which are being developed to overcome the diffraction limit of far-field optics, can exhibit NA $= 1.8$ or higher,[8,9] and therefore near-field systems can potentially increase data density in each layer.

A second primary factor in limiting data density is the undesired detection of data from layers other than the layer at the laser focus, which is an effect called *inter-layer crosstalk*. Confocal systems, which refer to optical systems that use a point detector, exhibit better crosstalk rejection than non-confocal systems.[10]

Figure 2 shows the detailed data mark pattern model used in this paper. T_z is thickness of a data layer. L_x, L_y, L_z are the data mark dimensions in the x, y, and z directions,

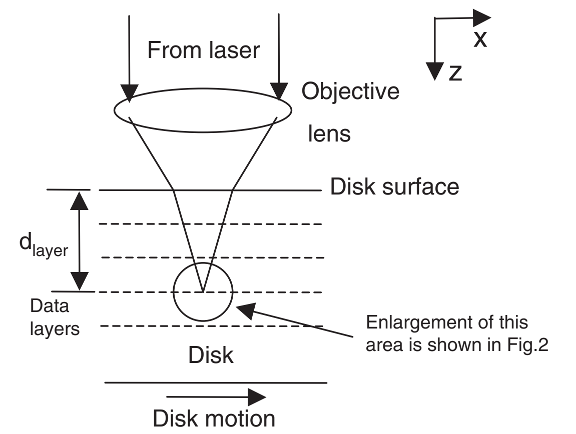

Fig. 1. A typical fluorescent volumetric read out system. The incident laser beam is focused by an objective lens onto a bit plane of interest at depth d_{layer} below the top surface. The distance between marks in the same bit plane is T_x, while the distance between two planes of data marks is T_z.

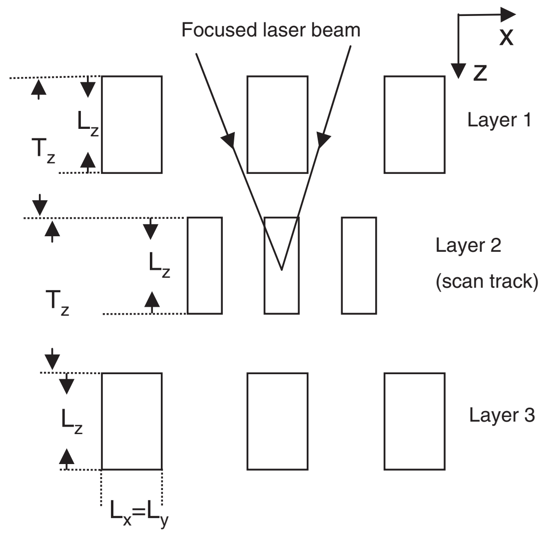

Fig. 2. Mark patterns used to simulate inter-layer crosstalk. Layer 2 contains the scan track. Mark depth is L_z. Layer 2 contains high-frequency data marks, while Layer 1 and Layer 3 contain a larger, low-frequency data marks.

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