

Super-Resolution by Combination of a Solid Immersion Lens and an Aperture

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(Received October 30, 2000; accepted for publication November 29, 2000)

A solid immersion lens is combined with various aperture shapes in order to improve resolution. Both metallic and dielectric apertures are investigated, and optimum shapes for each are determined. Fabrication techniques for each type of combination probe are discussed and implemented, and a simple experiment with a dielectric combination probe scanning a reflective grating demonstrates improved resolution compared to a solid immersion lens alone.

KEYWORDS: near-field optics; optical data storage; super resolution; solid immersion lens

1. Introduction

Two techniques used to reduce spot size in optical recorders are solid immersion lens (SIL) systems and aperture probes. In SIL systems, an auxiliary lens is placed in near contact with the recording layer. With aperture systems, light is forced through a hole that is smaller than the light spot illuminating it. SIL systems, while offering substantially improved spot size, do not have the resolution observed from aperture probes. However, aperture probes suffer from low signal-to-noise ratio. This paper presents a new idea based on the combination of a SIL and an aperture probe. The combination probe displays performance characteristics beyond those observed when the techniques are used separately.

The SIL was introduced by Mansfield and Kino¹⁾ in 1990 for use in high-resolution microscopy. In 1994, Terris²⁾ *et al.* introduced the SIL for optical recording. The basic SIL system is shown in Fig. 1. Light from a laser is focused on the recording layer by an objective lens. The SIL is a hemisphere that is image-centered, so light rays are not refracted at the SIL surface. Inside the SIL, the wavelength of the light is reduced, and a focused spot is produced that exhibits full-width at $1/e^2$ spot size s of approximately $s = \lambda/NA_{\text{EFF}}$, where $NA_{\text{EFF}} = n \sin \theta_m$, n is the refractive index of the SIL and θ_m is the marginal ray angle inside the SIL. Reflected light is collected by the objective and directed to the detectors. Systems recently reported include a GaP SIL with $NA_{\text{EFF}} = 1.98$ that was used with $\lambda = 690$ nm laser to produce $s = 328$ nm,³⁾ and another system that used $\lambda = 405$ nm and $NA_{\text{EFF}} = 1.5$ to produce $s = 270$ nm.⁴⁾

Aperture probes were introduced to optical storage by Betzig *et al.* in 1992.⁵⁾ In the Betzig design, an optical fiber is drawn to a small diameter of typically 100 nm. The fiber is coated with Al at the probe tip, with only a small hole at the aperture. The Al absorbs the exponential tail of the waveguide mode. Betzig's instrument was used to write 60 nm domains in magneto-topic material, but suffered from very low efficiency ($\sim 10^{-5}$), so the data rate was not comparable to commercial optical disks. Recently, new aperture designs promise higher throughput, but data rate for a single aperture is still very low.⁶⁾

An optical system that combines a SIL with an aperture exhibits certain advantages. The spot size s is mainly determined by the aperture size. Optical efficiency is greatly im-

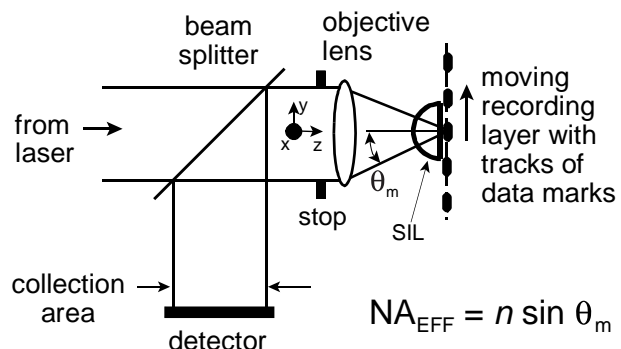


Fig. 1. Basic solid immersion lens (SIL) system. Laser light is focused by an objective lens onto a moving recording layer. The SIL, which is in near contact with the recording layers, reduces the wavelength by a factor of n and produces a small spot size. Reflected light is collected by the objective lens and directed to the detectors. The angular range of collected information is determined by the SIL, the objective lens, and the detector.

proved over the aperture alone, because the light spot illuminating the aperture is smaller than is possible with fiber-based or far-field illumination. A second fundamental advantage of the combination probe is in the detection process. In order to understand this improvement, consider the aperture-only system, where poor contrast is a result of the collection system not gathering enough spatial frequency information. As explained in the next section, the SIL-aperture combination provides a dramatic improvement in this regard. The following sections provide discussion on our fabrication techniques, experiment and conclusions from this work.

2. Detection

In order to understand a fundamental advantage of combining an aperture with a SIL, we review the detection process in terms of a simple scalar model. Figure 2 shows the detection process of the DVD system as an example. A profile of the focused spot $h(x, y)$ exhibits a spot size s . The angular-spectrum representation $H(\alpha, \beta)$ of the focused spot is found by the Fourier transform of $h(x, y)$. Coordinates of H are the direction cosines (α, β) corresponding to the (x, y) axes, respectively. $H(\alpha, \beta)$ is a representation of the light pattern in the exit pupil. The limits of $H(\alpha, \beta)$ correspond to the NA of the system.

Figure 2 shows the interaction of the mark pattern $m(x, y)$ and the spot $h(x, y)$ as a simple multiplication. The reflected-

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