High-performance readout and recording by a combination aperture

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A solid immersion lens combined with a conical dielectric tip exhibits good resolution and efficiency in reading and recording data marks on optical storage media. We demonstrate a combination aperture that produces ~200-nm full-width $1/e^2$ spot size and achieves 50% optical efficiency in an edge-scan experiment. A comparison of recording with the combination aperture, with an unmodified solid immersion lens, and with a far-field system is made. © 2001 Optical Society of America

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Both solid immersion lenses (SILs) and aperture probes are being developed as near-field techniques to be used in optical data storage systems.[1,2] SIL systems, although they offer substantially improved spot size, do not have the resolution that can be observed with aperture probes. However, aperture probes suffer from low throughput, limiting optical efficiency. We present a new technique that combines a SIL and a dielectric aperture probe. The combination aperture can achieve higher performance (in terms of spot size and efficiency) for optical data storage and microscopy than those observed when the SIL or the aperture probe is used alone.

The geometry of the combination aperture is basically that of a conical dielectric aperture probe attached to the bottom of a SIL with refractive index n_{SIL}.[3] As can be seen from Fig. 1, light of wavelength λ from an objective lens is focused on the base of a SIL at the aperture probe. The light then propagates to the recording layers. The bottom diameter of the probe is d, which is $\sim 0.5\lambda/n_{\mathrm{SIL}}$. Because of the use of a SIL, the focused spot that illuminates the aperture is smaller than that of a far-field system, thus causing improved transmission through the aperture. Owing to the small d of the probe, a small spot size is produced. The spot has approximately the same dimensions as the aperture, which are much smaller than those produced by the SIL system alone.[4]

It is also possible to fabricate a metallic aperture in combination with a SIL. Experimental results indicate that large background reflection from the metallic layer that surrounds the aperture limits the detectable signal. The background reflection from dielectric apertures is negligible, so these apertures are the focus of this research. Details of the design and the fabrication of both metallic and dielectric apertures can be found in Refs. 3 and 4.

To evaluate the combination aperture in optical reading, we use a phase grating of 1.6-μm pitch as a test object in an edge-scan experiment with a $\lambda = 488$ nm argon laser. Parameters for the combination aperture include $n_{\mathrm{SIL}} = 1.843$, $d = 200$ nm, and $\mathrm{NA}_{\mathrm{EFF}} = 2.4$, where $\mathrm{NA}_{\mathrm{EFF}}$ is the effective numerical aperture. The experimental setup is shown schematically in Fig. 2. Laser light is focused into the combination aperture by a 0.5-NA objective lens. Spacing between the combination aperture and the grating is controlled to ~40 nm by a small movement of a picomotor along the z direction as well as by a strain gauge attached to the SIL mount. The microscope stage, which holds the grating, oscillates along the x direction, thus making the focused light spot scan across the lands and grooves of the grating. The reflected light is then collected by the objective lens and directed by a relay lens to a CCD and a detector located at the pupil plane conjugate to the stop. The detector has two segments (A and B), which can provide electrical voltage as a result of the sum and difference of the light levels detected at A and B.

Two aspects of the readout experimental results are studied. One is the pupil modulation pattern captured by the CCD. The other is the readout signal generated by the detector. When the grating translates along the x direction, the pupil modulation patterns for the far-field system, the SIL system, and the combination aperture system are as shown in Figs. 3, 4, and 5, respectively. In Figs. 3 and 4, the pupils show a typical overlap pattern that is due to diffraction from the 0th and ±1st orders of the grating. The 0th diffracted order fills the pupil entirely, whereas the ±1st diffracted orders appear as sections of circles displaced on opposite sides of the 0th order. Modulation in the pupil occurs where the ±1st orders overlap the 0th order. Comparing Figs. 4 and 3, we find that the SIL

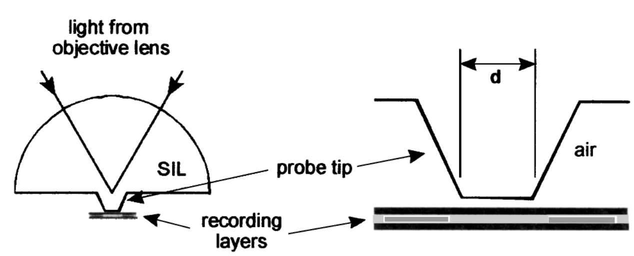

Fig. 1. Geometry of a combination aperture.

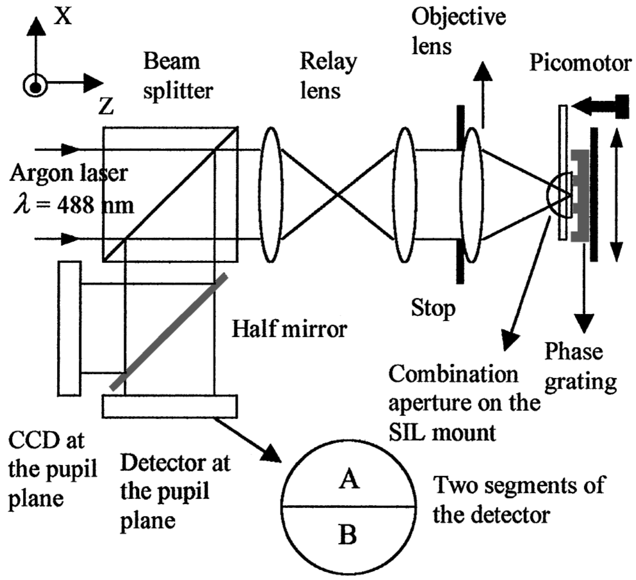

Fig. 2. Setup of an edge-scan experiment.

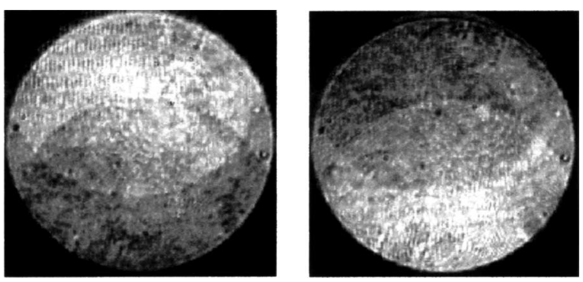

Fig. 3. Two distinct pupil images from the far-field system (NA = 0.5) when the grating is translated.

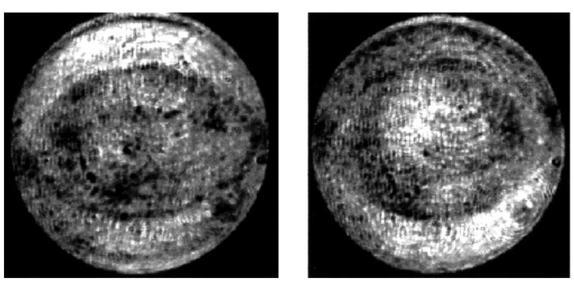

Fig. 4. Two distinct pupil images from the SIL system (NA_{EFF} = 0.95) when the grating is translated.

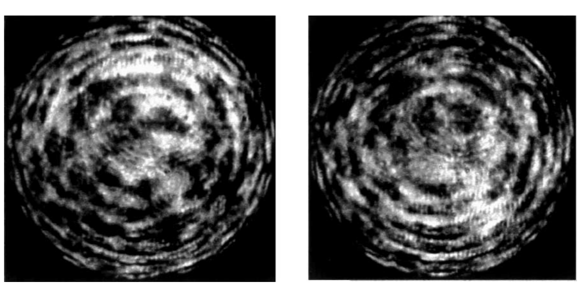

Fig. 5. Two distinct pupil images from the combination-aperture system (NA_{EFF} = 2.4) when the grating is translated.

In Fig. 5, a unique pupil modulation pattern from the combination aperture system is shown. Compared with that of Figs. 3 and 4, the boundary of the ±1st order is less clear, because the spatial limits imposed by the aperture produce a wider angular spectrum in the pupil, as described in Ref. 5. Therefore a larger area of modulation is observed, and higher contrast results. However, the experimental pupil patterns shown in Fig. 5 are more complicated than can be predicted by simple theory. Further investigation to describe this effect is continuing.

The readout signals from the difference A − B are shown in Fig. 6, which includes output from the far-field, SIL, and combination-aperture systems. The combination-aperture system gives the best improvement in readout performance, because the signal has the sharpest rise when it is scanning over the edge of the grating. The full-width $1/e^2$ spot size for the combination system is ~200 nm, and we find it by estimating the scan distance between the 5% and 95% heights of the signal. The 200-nm spot system has larger overlap on the pupil and provides stronger modulation than the far-field system does.

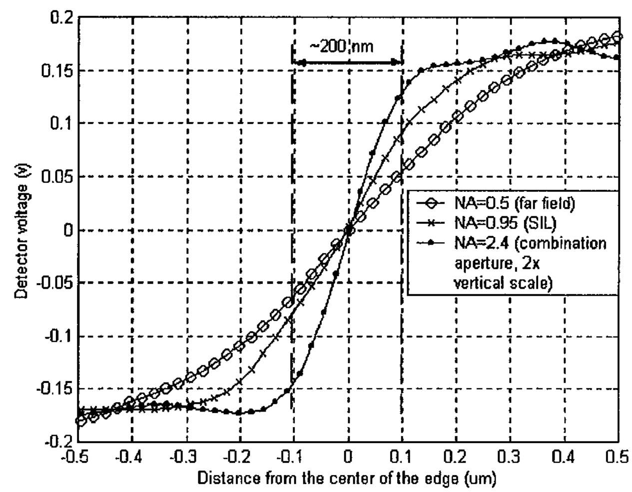

Fig. 6. Readout signals from far-field, SIL, and combination-aperture systems during testing of a phase grating with 1.6-μm pitch.

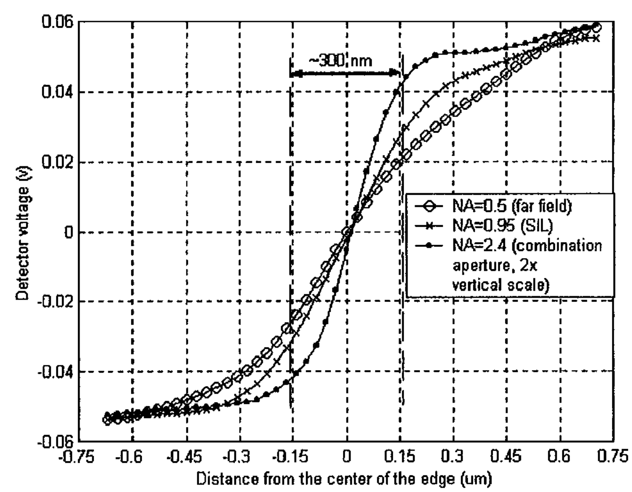

Fig. 7. Readout signals from far-field, SIL, and combination-aperture systems when a big mark is scanned on the phase-change medium.

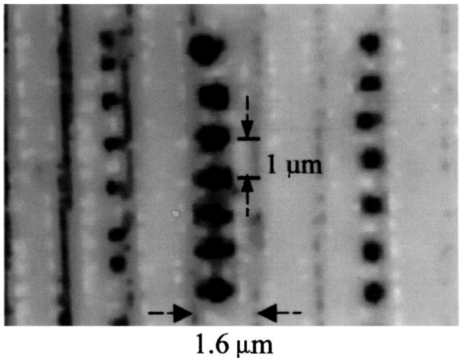

Fig. 8. Three series of marks written along the vertical tracks of a phase-change medium by (left to right) the combination-aperture, far-field, and SIL systems.

size agrees well with the aperture size of 200 nm. In addition, because the vertical signal produced by the combination aperture has a 2× scale, the signal loss from the system is only 50% in reflection. Figure 7 gives the readout signals from the sum A + B when a large mark written on a phase-change medium is used as a test object. It shows an ~300-nm full-width $1/e^2$ spot size and 50% efficiency in reflection from the combination aperture system. The 300-nm spot size is larger than that obtained from the phase grating because the scan was taken over a groove, where the air gap is 100–200 nm.

To demonstrate the capability of the combination aperture for high-density recording, we replaced the test grating with a phase-change medium. In addition, the laser beam was modulated in 1-s pulses and 1 mW of power out of the objective lens to write marks. The microscope stage was moved along the track as marks were written.

Figure 8 shows the recorded marks imaged by a visible-light microscope. As shown in the figure, three series of marks were written, spaced ~1 μm along the vertical tracks of a phase-change medium. Mark diameters from the far-field, SIL, and combination-aperture systems were 750 nm ± 80 nm, 500 nm ± 60 nm, and 300 nm ± 60 nm, respectively. We measured the mark widths by determining the width of the mark with respect to the known track pitch of 1.6 μm. Precision of the measurements was limited by the resolution of the optical microscope and by variability in the written marks. The point-spread function of the microscope, because of its 0.8-NA objective lens and 500-nm mean wavelength, was not deconvolved to reduce the mark size reported above. The combination-aperture system demonstrates better potential for high-density recording than the far-field and SIL systems.

In summary, we have used a combination-aperture system for optical reading and recording with a $\lambda = 488$ nm argon laser. For optical reading, a unique pupil image, a resolution of 200-nm full-width $1/e^2$ spot size, and an optical efficiency of 50% were obtained when we scanned a phase grating of 1.6-μm pitch. For optical recording, a series of ~300-nm-diameter marks was written on a phase-change medium; the marks were smaller than those written by the far-field and the SIL systems with the same laser pulse.

Extensions of probe technology to smaller apertures, as well as applications in other disciplines such as biology, are active areas of our research. In general, we have found that smaller apertures do not significantly reduce spot size, whereas the transmission is efficiently decreased. Larger apertures have slightly higher transmission efficiency, but they have larger spot sizes. The results tend to scale with wavelength.

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