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Predictive aberration correction for multilayer optical data storage

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The recording of data in multiple layers, rather than a single layer, permits a significant increase in the capacity of optical data storage devices. However, focusing to the different layers introduces different amounts of depth-dependent aberrations. Variable aberration correction is therefore necessary to maintain diffraction-limited operation. We demonstrate the use of adaptive optics to predict and correct these aberrations for both the recording and read-out of such media. [DOI: 10.1063/1.2166684]

The quest for high density data storage devices has lead to the proposal of three-dimensional (3D) optical memories as potential successors to the ubiquitous compact disk and digital versatile disk and the recently introduced BluRay disk technologies. Rather than writing data in a single plane, the data are written in a number of layers in a suitable recording substrate. Although different recording media have been suggested (for example photorefractive,[1] photochromic,[2] or fluorescent media[3]), they all suffer from the same problem that affects both the recording and read-out of these devices: aberrations. The practical requirement that dry objective lenses must be used combined with the desire to use the highest aperture to minimize the size of the written data means that significant amounts of spherical aberration are introduced, a problem that is exacerbated as one focuses further into the recording medium. Moreover, a misalignment of the storage medium with respect to the optic axis results in the introduction of a combination of coma and astigmatism. All of these aberrations conspire to blur the focal spot, increasing the volume of the written bit, decreasing the resolution of the read-out system and effectively limit the number of useable layers of data in the medium.

Several recent developments in 3D optical data storage have used femtosecond pulsed lasers to induce multiphoton absorption effects. The nonlinear dependence of the multiphoton process on the light intensity means that the change of optical properties of the recording medium is confined to a small region. Bit data can therefore easily be written in closely spaced layers, permitting higher recording densities. This is in contrast to single-photon phenomena, wherein the change in optical properties of the material occurs throughout the focusing cone and the resulting written bits are larger. Read-out of the data is typically performed using an optical system similar to the confocal microscope. The confocal microscope is a point scanning microscope that employs a pinhole in front of the photodetector to obscure all light from the specimen except that from the focal spot.[4] In this way it only images a thin layer of the specimen and does not "see" the out-of-focus parts. As such, confocal optical systems are ideal for the read-out of three-dimensional optical memory devices.

Both the recording and read-out processes suffer from the effects of aberrations. It is important to note the way in which the induced aberration affects these two processes. Writing data involves only a single pass of the light, into the substrate. It has been shown that aberrations introduced here can be compensated by preshaping the light with an equal but opposite aberration, ensuring an aberration-free focal spot.[5] The confocal microscope read-out, on the other hand, involves first the illumination of the bit data, the beam passing into the substrate, then the passage of light back out of the substrate. For read-out, aberrations are introduced into both paths and therefore aberration correction is necessary in both paths.[6]

We propose the use of adaptive optics to overcome these problems. The techniques of adaptive optics were first developed for use in astronomical telescopes in order to compensate aberrations introduced by atmospheric turbulence.[7] The techniques were later used in other applications such as ophthalmology[8] and microscopy.[6] In principle, an adaptive optics system consists of a method for measuring aberrations, an adaptive element for aberration correction and a control system. The aberration correction element would usually be a deformable mirror or a liquid crystal device. Figure 1 shows the adaptive optics system we employed.

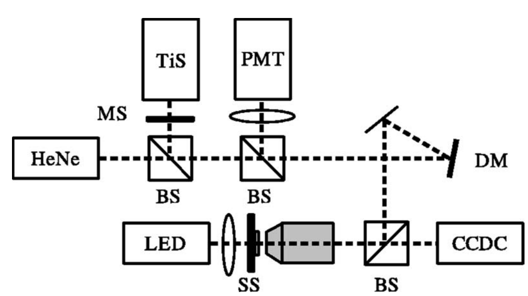

FIG. 1. Schematic of the experimental system. Some intermediate lenses have been omitted for clarity. Key: HeNe—helium-neon laser, TiS—titanium-sapphire laser, PMT—photomultiplier tube, DM—deformable mirror, CCDC—CCD camera, BS—beam splitter, MS—mechanical shutter, SS—scanning stage.

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This incorporated a titanium-sapphire laser (Coherent Mira, center wavelength 780 nm, pulse length 150 fs) for writing data and a helium-neon laser (Melles Griot, 633 nm) for read-out. A three-dimensional piezo stage (Piezosystem Jena) was used for positioning and scanning of the recording medium. A green light-emitting diode (Lumileds) was included to allow transmission images to be captured by a CCD camera. The read-out signal was detected by a photomultiplier tube placed behind a confocal pinhole with diameter equivalent to 67% of the Airy disk. Aberration correction was implemented using a membrane deformable mirror (DM) (OKO Technologies, Netherlands). When focusing perpendicularly through a refractive index mismatch, as is the case with 3D optical memory, only spherical aberration is present. This can be represented by a rapidly convergent series of rotationally invariant Zernike polynomials. The aberration is dominated by the lowest-order spherical aberration mode and removal of this aberration mode is sufficient to improve performance of the system over significant depth.[9] The control signals required to operate the DM in order to remove this spherical aberration mode were obtained using an interferometric method similar to that described by Booth *et al.*[10]

In order to demonstrate the adaptive optics system we used multilayer recording media consisting of several photosensitive layers separated by inert spacing layers. The 8-μm-thick spacers were pressure sensitive adhesive layer, whereas the 1.5-μm-thick recording layers consisted of poly-(methylmethacrylate) doped with 1,3,3,-Trimethylindolino-6'-nitrobenzopyrylospiran, a dye that absorbs in the UV. The recording medium was mounted behind a 110 μm thick cover glass with a layer of glycerol for refractive index matching in order to reduce reflections from the upper surface. The unwritten recording layers were imaged in the adaptive confocal microscope using an oil immersion objective lens (Zeiss Apochromat, 1.3 numerical aperture, 40×). The amount of spherical aberration correction required for diffraction-limited imaging varies as the focusing depth is changed. The required correction can be obtained by optimizing the confocal microscope signal from a reflection off a surface in the recording medium. The presence of spherical aberration results in a reduced maximum signal. By adjusting the amount of correction, we could find the optimum setting for any particular layer. This was performed for the top and bottom layers of the recording medium. Since the variation in spherical aberration is known to be linear in focusing depth (in a homogeneous material), we could interpolate to get the optimum correction for any intermediate layer.

Figure 2 shows images of the stack of recording layers for different aberration conditions. For each recording layer, two reflections should be visible: one from the top and one from the bottom surface of the 1.5 μm thick layer. The group of images on the left of Fig. 2 were obtained using the optimum aberration correction for the top layer, which is clearly imaged. The images of the other layers, situated deeper in the recording medium, are noticeably aberrated and the two reflections are no longer distinct. The three insets show enlarged detail of the 1st, 10th, and 20th layers, counting from the top of the specimen. The group of images on the right of Fig. 2 was obtained using varying aberration correction that was optimized for each individual layer. In this case, each layer is much more clearly imaged and for all layers the two separate reflections are clearly visible. We attribute the overall drop in reflected signal as one focuses deeper to a combination of reflective and absorptive losses and residual aberrations.

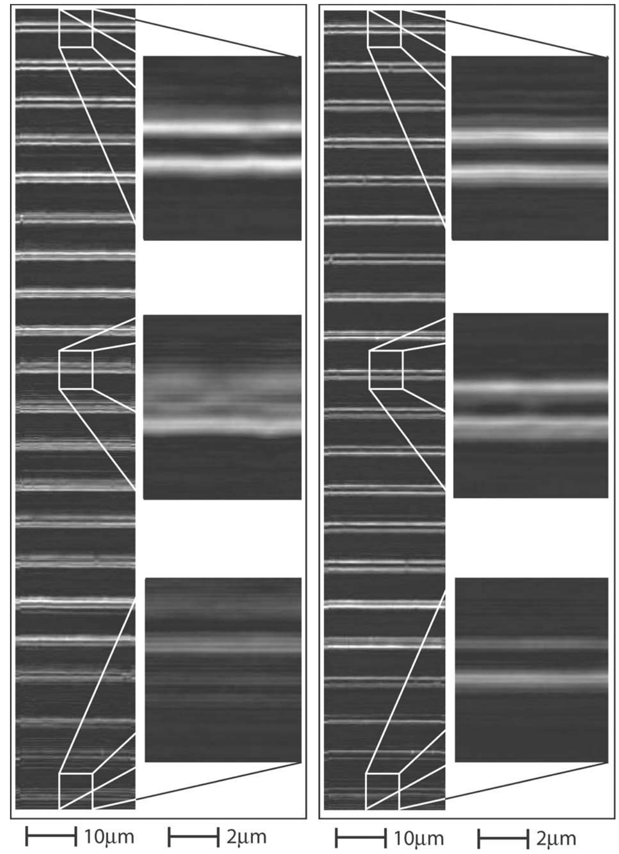

FIG. 2. Axial section confocal microscope scans of the whole multilayer recording medium with detail shown for the 1st, 10th, and 20th layers. The aberration correction was fixed at the level required for the top layer (left) and adapted for each individual layer (right). The optical axis is oriented down the page in these images.

By taking advantage of nonlinear optical effects, it is possible to confine the written bit data to the focal spot of the objective lens. The data can therefore be written easily in a particular layer of the storage medium without affecting the adjacent layers. However, since aberrations reduce the focal spot intensity, the efficiency of a nonlinear process is considerably reduced. This may result in a negligible local change in optical properties and unreadable data. Although one could restore the intensity by increasing the laser power, the aberrations would cause an increase in focal spot size, particularly in the axial direction. This, in turn, would lead to an increase in the required layer spacing and a corresponding reduction in storage density. Figure 3 shows the effect of aberrations by writing bitwise data deep into the layered storage medium. The data, represented by an array of dots, were recorded in the form of voids created in the 19th layer, near the bottom of the recording medium. The femtosecond-pulsed titanium-sapphire laser was used as the light source, the power at the objective lens pupil was approximately 20 mW and the exposure time was 200 ms. The spacing between the recorded dots was 1.5 μm. When the aberration correction was turned off (i.e., set to the equivalent correction for the uppermost layer), no bits were written.

These results show how depth-dependent aberrations in a multilayer optical data storage system can be corrected using adaptive optics. Benefits are obtained for both the recording and read-out processes. In practical systems, where

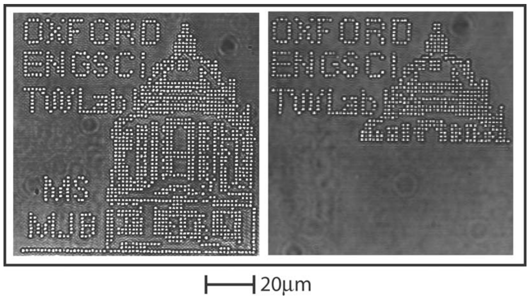

FIG. 3. Transmission images demonstrating aberration correction for recording data. The data were recorded as an array of dots (including a representation of the Radcliffe Camera building in Oxford). Left-correction on during the whole writing process. Right-for the second half of the writing process the aberration correction was switched off.

dry objective lenses are required, the aberrations are larger and the optical effects would be more severe. In this case, predictive aberration correction would significantly extend the functional depth of both the recording and read-out systems.

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