Adaptive optics for three-dimensional optical data storage and micromachining

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Introduction

The quest for high density data storage devices is driving research into three-dimensional optical memories - successors to the ubiquitous compact disk (CD), digital versatile disk (DVD) and BluRay 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, photochromic, or fluorescent media) 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 high aperture lenses to minimise the size of the written data means that significant amounts of spherical aberration are introduced, a problem which 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 limiting the number of useable layers of data in the medium. Aberration correction through adaptive optics presents a solution.

Several recent developments in optical data storage technologies have used femtosecond pulsed lasers to induce multi-photon absorption effects. The non-linear dependence of the multi-photon process on the light intensity means that the optical effects are confined within the focal spot and the change of optical properties of the recording medium is confined to a small region. This is in contrast to single photon phenomena where the change in optical properties of the material occurs throughout the focusing cone. Bit data can therefore easily be written in closely spaced layers permitting higher recording densities. Read out of the data is typically performed using a confocal microscope. The confocal microscope is a point scanning microscope that employs a pinhole in front of the photodetector that obscures all light from the specimen except that from the focal spot. In this way it only images a thin layer of the specimen and does not ‘see’ the out of focus parts. As such it is 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 pre-shaping the light with an equal but opposite aberration, ensuring an aberration free focal spot[1). 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. So for read-out, aberrations are introduced into both paths and therefore aberration correction is necessary in both paths. We have constructed an adaptive optics system that can correct these aberrations thus increasing the depth at which data can be recorded and read-out. This system was also used to demonstrate the problem of aberrations in optical micromachining.

The adaptive optics system

Figure 1 shows the adaptive optics system. The system 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 LED (Lumileds) was included to allow transmission images to be captured by a CCD camera.

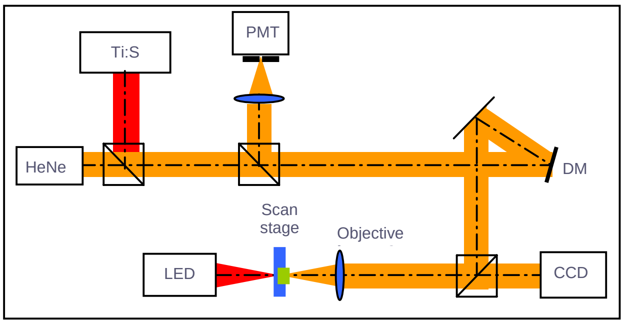

Figure 1. Schematic of the experimental system. Some intermediate lenses have been omitted for clarity. Key: HeNe - helium neon laser, TiS – titanium-sapphire laser, PMT - photon multiplier tube, DM - deformable mirror.

Aberration correction

Aberration correction was implemented using a membrane deformable mirror (DM) (OKO Technologies, Netherlands). This device consisted of an aluminium coated silicon nitride membrane suspended above an electrode array. The surface of the mirror was deformed by the application of voltages between the electrodes and the membrane. In general, an aberration in an optical system with circular pupils can be described by a series of Zernike polynomial modes. These form a set of orthonormal functions, defined over a unit circle, and correspond closely to the ‘traditional’ aberrations, such as spherical aberration, astigmatism and coma. Rather than drive the individual DM electrodes directly, the usual approach is to use such a modal basis. We obtained the combinations of control signals required to generate these aberration modes using an interferometric training scheme (unpublished results; reference[2)] describes a complementary method). When focusing through a refractive index mismatch, as is the case with 3D optical memory, only spherical aberration is present. This is 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 optical memory system over significant depth[3)].

Confocal microscope readout

In order to demonstrate the adaptive optics system we used multi-layer recording media consisting of several photo-sensitive layers separated by inert spacing layers. The 8 µm thick spacers consisted of PMMA whereas the 1.5 µm thick recording layers were a mixture of PMMA and 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 specimen was imaged in the adaptive confocal microscope using an oil immersion objective lens (Zeiss Apochromat, 1.3 NA, 40x). 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 the effects of the aberrations on the imaging of the different layers. The images on the left of Figure 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. The images on the right of Figure 2 were obtained using varying aberration correction that was optimised for each individual layer. In this case, each layer is much more clearly imaged.

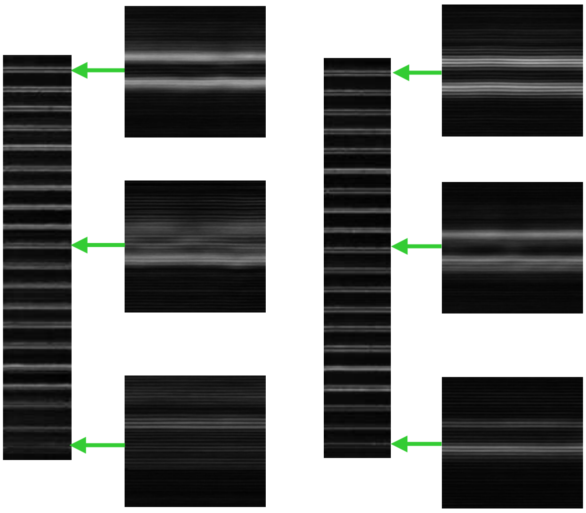

Figure 2. Axial section confocal microscope scans of the whole multi-layer recording medium with detail shown for the 1st, 10th and 20th layers. The optical axis is oriented vertically in these images.

Aberration corrected recording

By taking advantage of non-linear 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 non-linear process is considerably reduced. This may result in a negligible 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 were recorded in the form of voids created in the 19th layer, near the bottom of the recording medium. A square array of 10x10 dots (omitting the diagonal elements) was written. The fs-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.

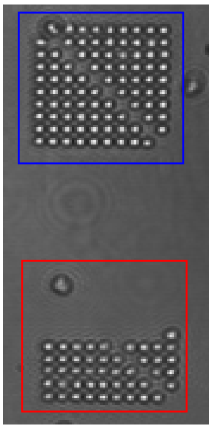

Figure 3. Transmission image demonstrating aberration correction for recording data. Blue box – correction on during the whole writing process. Red box - For the first half of the writing process the aberration correction was switched off.

Micromachining

Such aberration correction could also benefit micromachining systems where such voids are written using non-linear processes. For example, the production of three-dimensional microfluidic devices requires the precision machining of channels within the bulk of a material. Again, the focusing is affected by aberrations and the depth of accuracy of machining could be significantly increased with the use of adaptive aberration correction. Figure 4 shows an example of aberration correction for the machining of channels in the polymer substrate. This pattern was recorded in the 11th layer of the multi-layer medium with the appropriately determined aberration correction. The figure was created by a sequence of pointwise, overlapping exposures such that the individual voids combined to produce continuous channels. The image on the left shows the pattern with the aberration correction on. For the lower half of the second figure, the aberration correction was switched off and no machining effect is visible.

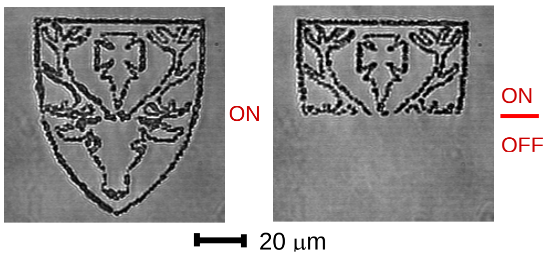

Figure 4. Transmission microscope images of a micromachined figure (the crest of Hertford College, Oxford). In the bottom half of the right hand figure, the aberration correction was turned off and no voids were written.

Acknowledgements

We are grateful to Prof. Y Kawata of Shizuoka University, Japan for providing the layered recording media. MJB is a Royal Academy of Engineering/EPSRC Research Fellow. MS is supported by the DAAD (German Academic Exchange Service).

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