3-D Optical Storage and Engraving Inside Transparent Materials[†]

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Abstract. We present a novel method for 3-D optical data storage and internal engraving that has sub-micron resolution, provides a large contrast in index of refraction, and is applicable to a wide range of transparent materials.

Three-dimensional optical data storage offers the potential for very large recording capacity and has the possibility of parallel read-out. High density recording has been demonstrated in a photopolymer using two-photon absorption [1]. Here we report a novel method for 3-D optical data storage that does not require a photosensitive material, has submicron-size resolution, provides a large contrast in index of refraction, can be read out under a standard microscope. This method is applicable to a very wide range of materials including fused silica, various glasses, sapphire, ionic crystals, and plastics, thus allowing for a storage medium that is mechanically, chemically and thermally very stable, and inexpensive. The method can also be used for engraving very fine-scale patterns inside transparent materials.

We tightly focus an ultrashort laser pulse of proper energy inside a transparent medium to produce very localized structural changes, which result in a strongly modified index of refraction. This process is used to record digital information in a 3-D pattern, by translating the medium relative to the focal point of the beam. Figure 1 shows an example of a random binary pattern stored inside fused silica, recorded using 0.5-μJ, 100-fs, 780-nm pulses from an amplified Ti:Sapphire laser, focused by a 0.65 numerical aperture (NA) microscope objective. The image is read out using transmitted light in a microscope with a 0.95 NA objective. The spacing between adjacent bits is 2 μm. The written spots can be viewed as dark or bright points depending on the position of the read-out objective. This could be used as a focusing and a contrast enhancing feature in a read-out system. During read-out, the depth discrimination provided by the short depth-of-field of the 0.95 NA objective is sufficient if adjacent layers are spaced by about 10 μm or more. More densely spaced patterns could be read out using (serial) scanning techniques such as confocal or DIC laser microscopy, but the inter-layer spacing is still limited by the longitudinal extent of the structurally altered regions, which is about 2.5 μm. Smaller diameter and shorter length features should be possible if an objective with NA>0.65 is used. We recorded 10 layers spaced by 15 μm, using a standard 0.65 NA refractive objective. Using a reflective objective with a large working distance and an adjustment for aberrations caused by focusing into the material, it should be possible to record over 100 layers, spaced by 10 μm.

Figure 2 shows a SEM image of a 5x5-μm regular array of spots recorded under conditions identical to those used in Fig. 1, polished down to the written layer. The

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bright spots in this angled view correspond to protrusions on the surface, while the dark spot (top row second from the right) corresponds to a cavity in the surface, as verified with an atomic force microscope (AFM). A typical cavity is shown at higher magnification in the inset of Fig. 2. This differs drastically from the much larger, cracked and irregular features produced by 200-ps and 10-ns pulses.

Energy from the ultrashort laser pulse is coupled into the material through a combination of multi-photon absorption and avalanche ionization [2], creating a 'micro-explosion'. Unlike ultrafast surface damage experiments however, ablation is not possible since the excited region is internal to the material. At the focus, nonlinear absorption can create an excited region much smaller than the linear intensity distribution, making submicron-size features possible even significantly above the energy threshold of 0.3 μJ. The ultrafast energy deposition creates very high temperatures and pressures inside the region; material is ejected from the center and forced into the surrounding volume, leading to the formation of a structure consisting of a void surrounded by densified material. This mechanism is consistent with the SEM and AFM observations: the protrusions suggest the creation of denser, harder material, more resistant to the mechanical polishing; deeper polishing reveals a pit corresponding to a void (or at least less dense material) which is created at the center of the micro-explosion.

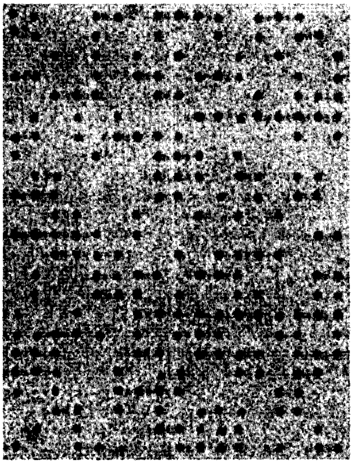

Fig. 1 Microscope photograph of a binary pattern stored inside fused silica with 2-μm bit spacing.

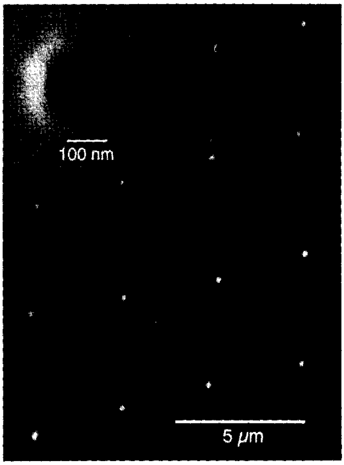

Fig. 2 A tilted SEM view of a polished cross-section through a regular array of bits with 5-μm spacing.

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