Three-dimensional patterned media for ultrahigh-density optical memory

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We report a recording medium in which a three-dimensional nanoscale structure can be photofabricated for multilayered optical memory using a two-photon process. By fabricating the structures in the medium, we can control the shape of recorded bits and, in effect, their spatial frequency distribution. We succeeded in recording bits with a 0.5 μm interval in any particular plane and 2.0 μm interval between successive layers. Thus, storage density of 2.0 Tbits/cm^3 is achieved. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1771800]

Recently, various techniques have been developed to achieve high density in optical memories. Near-field optics can reduce the mark size of individual bits[1–4] and holographic storage techniques can record data in three dimensions of a medium.[5,6] Multilayered optical memory is also one of the most promising techniques.[7–13] It retains the removability and durability of current optical memories and many existing techniques. In addition to it, the instrumentation used in optical pick-up heads, servo control, autofocusing, tracking etc. can be applied to multilayered optical memories after some modifications.

In this letter, we present the fabrication of a three-dimensional (3D) nanopatterned recording medium for multilayered optical memory. By fabricating the structures in the recording medium, we can control the spatial frequency distribution of recorded bits that can be simultaneously optimized for the readout system.

Figure 1(a) shows the recording process in a structured medium using two-photon excitation. The z axis represents the axial direction of focused light and the x and y axes lie in the plane of the recording layer. Figures 1(b) and 1(c) present the spatial frequency distributions of a recorded bit in the S_x–S_y and S_x–S_z planes, respectively. In this case the recording areas are arranged in the form of hexagonal arrays. Since the shape of a recorded bit in a structured medium is determined by the product of squared intensity of the focused beam and the structure of the patterned medium, its frequency distribution is given by convolution of the frequency distribution of the squared spot intensity and that of the patterned medium. As a result, each individual bit in the patterned media contains higher spatial frequency components. Figure 1(d) shows the recording process in a plain medium for comparison. Figures 1(e) and 1(f) show the frequency distribution of a bit recorded in the plain medium along the S_x–S_y and S_x–S_z plane, respectively. The cutoff spatial frequency of a bit in a structured medium is 1.8 times higher in the x direction and 1.6 times higher in the z direction than that in a plain medium.

Extension of the distribution in the axial (S_z) direction is advantageous for the readout system of multilayered memories, since a reflection-type confocal microscope configuration may be used for the purpose. It has already been established that the high axial resolution and compactness of the reflection-type confocal microscope make it very promising as a readout system of multilayered optical memories.[14–16] According to Wilson *et al.*,[17] the spatial frequency distribution of a recorded bit in a plain medium does not overlap the optical transfer function (OTF) of the reflection-type confocal microscope. On the contrary, the spatial frequency distribution of a bit recorded in the 3D patterned medium easily overlaps the OTF, since the distribution is extended in the axial direction.

The recording density can also be increased by using 3D patterned media. When a bit is recorded in a patterned medium, its size may be restricted to a value smaller than that of the focused spot. As a result, we can reduce the interval between individual bits in a plane as well as in the axial

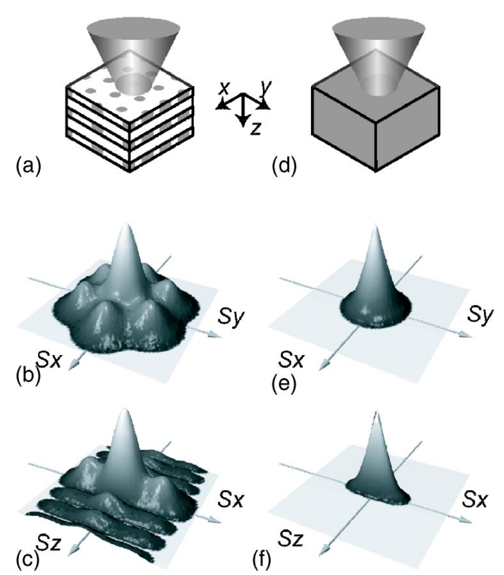

FIG. 1. Bit recording process and spatial frequency distribution of a recorded bit in structured as well as plain media. (a) Bit recording process in a structured medium. (b), (c) Spatial frequency distribution of a recorded bit in a structured medium along the S_x–S_y and S_x–S_z planes, respectively. (d) Recording process in a plain medium. (e), (f) Spatial frequency distribution of a recorded bit in a plain medium along the S_x–S_y and S_x–S_z planes, respectively.

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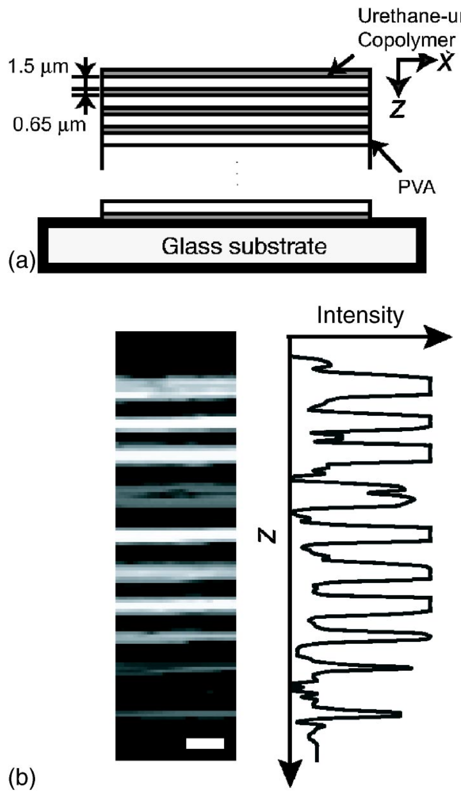

FIG. 2. (a) Structure of the multilayered recording medium. (b) Axial response of the multilayered medium observed with a reflection-type confocal microscope. The scale bar is 2.0 μm.

direction. The reduction of bit interval is more effective in the axial direction, because the full width of the half maximum of a focused spot along the axial direction is roughly three to four times longer than that along the *x* or *y* direction.

We fabricated the 3D patterned medium using spin coating and photobleaching techniques. First, photosensitive layers and transparent layers are piled up alternately by spin coating and form a multilayered recording medium. Next, we induced photobleaching of photosensitive layers with ultraviolet light or two-photon excitation of near-infrared light. The structure in a particular layer is formed by scanning the focused spot or by interference of multiple beams.

Figure 2(a) shows the structure of a multilayered recording medium developed by us. We used urethane–urea copolymers as photosensitive layers and polyvinyl alcohol (PVA) as transparent layers. Generally, it is difficult to pile up two different organic thin films, but we found that the urethane–urea copolymer and PVA do not interfere with each other nor detach from the interfaces.

Figure 2(b) shows the axial response of the multilayered medium observed with a reflection-type confocal microscope. Ten recording layers were clearly detected. The thicknesses of the photosensitive layers and the transparent layers were 0.65 and 1.5 μm, respectively. Each layer is clearly observed with a high contrast of 0.71.

A mesh-like pattern was fabricated in the recording layers by scanning a focused beam of light in three dimensions with a three-axis translation stage. We used near-infrared radiation of wavelength 790 nm from a Ti:sapphire laser (pulse width of the laser is 80 fs) and applied the two-photon process for photofabrication. Spacing of the vertical and transverse lines was 0.5 μm. A shutter and the three-axis translation stage were controlled with a computer to record sequential bit data. An oil immersion lens of numerical aperture (NA) 1.3 was used in order to reduce the spherical aberration that is generated by the refractive-index mismatch between air and the medium when the laser beam is focused in to deep layers.

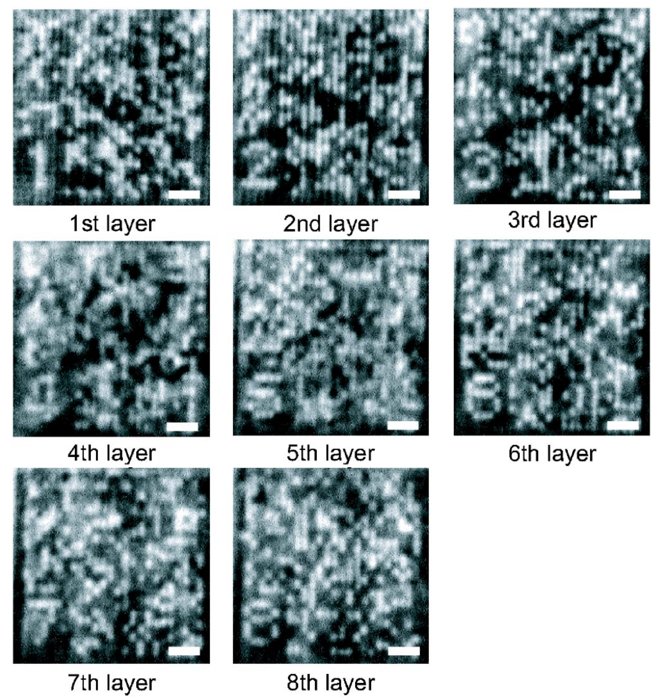

FIG. 3. View of recorded bit patterns in different layers of the 3D patterned medium. The bit interval in the transverse direction is 0.5 μm. The spacing of neighboring recording layers is 2.0 μm. Thus, a storage density of 2.0 Tbits/cm^3 is achieved. The scale bars are 2.0 μm.

For reading data, a helium–neon (He–Ne) laser was used as the light source. The wavelength was selected to be 633 nm, since the photosensitive material has no absorption in the red region. A pinhole was placed in front of the detector to make a confocal microscope configuration. The diameter of the pinhole was 30 μm.

Figure 3 shows the readout data recorded in different layers of the multilayered optical memory. Random bit data were recorded in eight layers and read out with high contrast. The bit interval was 0.5 μm. Since the medium had 3D patterned structures, each bit was square shaped and separated clearly from one another. The separation between the photosensitive layers was 2.0 μm. The separation was 2.8 times as large as the full width of the half maximum of the focused spot. Thus, a storage density of 2.0 Tbits/cm^3 was achieved using the 3D patterned medium.

We compared the readout signal from bits recorded in a patterned medium with that in a plain medium. Figures 4(a) and 4(b) show cross sections of readout data recorded in a patterned medium and a plain medium, respectively. The bit recorded in the patterned medium was sharper than that in the plain medium. The bias signal is smaller and the cross section of bits was square in shape. The square shape implies that the bits recorded in the patterned medium have higher spatial frequency components. The contrast of the readout signal shown in Fig. 4(a) was 0.74 and it is 1.2 times higher than that shown in Fig. 4(b).

We proposed a 3D patterned medium for three-dimensional optical memories. The medium provides higher

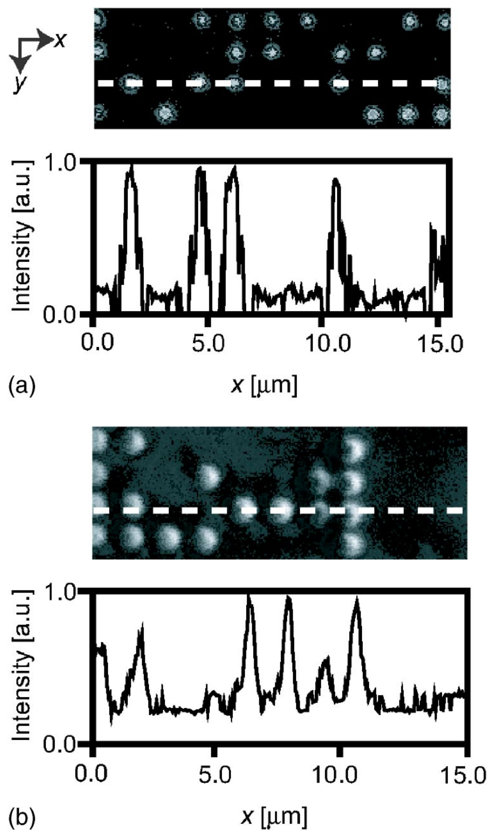

FIG. 4. Comparison of readout signals with a reflection-type confocal system from a (a) patterned medium and (b) plain medium.

contrast readout and higher density recording than a plain medium. We demonstrated that a recording density of 2.0 Tbits/cm^3 is achievable using this 3D patterned medium. To the best of our knowledge, this recording density is one of the highest among multilayered optical memories reported so far.

We used a laser-scanning technique to make the pattern in any particular layer. The technique is time consuming. The use of a nondiffracting Bessel beam or interference of multiple beams is promising in order to produce a 3D structure in recording media.

The structures fabricated in the medium are exactly the same as photonic crystal structures. It may be interesting to introduce photonic crystal properties like control of light propagation and localization of light into multilayered optical memories. The use of self-assembling materials is also promising in producing 3D patterned media.[18]

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