# Randomly accessible, multilayered optical memory with a $Bi_{12}SiO_{20}$ crystal

Yoshimasa Kawata, Takuo Tanaka, and Satoshi Kawata

A read-and-write, randomly accessible, multilayered optical memory with a $Bi_{12}SiO_{20}$ crystal as the medium is demonstrated. Data are recorded in the crystal as an absorption change that is due to the photochromic effect. These data are successfully recorded, read, and selectively erased in five layers in the crystal. The axial-separation distance between neighboring layers is 30 μm, and the lateral distance between bits is 5 μm. Selective bit erasure of the data is accomplished by illumination of the recorded bit datum with He–Ne laser light. To our knowledge, this is the first successful demonstration of the selective optical erasure of the photochromic effect in a BSO crystal. © 1996 Optical Society of America

## 1. Introduction

Recently, multilayered optical memories have been developed[1–5] to overcome the limitations of storage density associated with conventional optical memories such as compact disks or magneto-optic disks. Unlike conventional optical memories, data in multilayered optical memories are recorded throughout the volume of the medium. If, for example, we record 10 or 20 layers of data, we can achieve 10 or 20 times higher storage levels than those of current optical memories. We have already succeeded in recording 30 layers of data in photopolymer[6] and 10 layers of data in the photorefractive $LiNbO_3$ crystal.[7]

In this paper, we describe the use of a $Bi_{12}SiO_{20}$ (BSO) crystal as the recording medium for a multilayered optical memory. A bit datum in the crystal is recorded as an absorption change resulting from the photochromic effect and not as a refractive-index change, as is seen in $LiNbO_3$ crystals.[4,7] The BSO crystal was chosen because its physical properties and potential device capabilities have been studied extensively.[8,9] Furthermore, the crystal is easy to grow compared with other photorefractive crystals, which makes it suitable for mass production as a memory medium.

The authors are with the Department of Applied Physics, Osaka University, Suita, Osaka 565, Japan.

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## 2. Recording and Reading Data in a BSO Crystal

Figure 1 shows the optical setup for a multilayered optical memory with a BSO crystal. The setup is basically the same as a laser scanning microscope. An argon-ion ($Ar^+$) laser source is used for recording data, a white light source together with a CCD camera for reading, and a He–Ne laser source for erasing. The BSO crystal is placed on a three-axis stage (3-D scanning stage) controlled by a computer. A condenser lens is used to converge the light at a point in the crystal.

To record a bit datum in the crystal, the absorption change caused by the photochromic effect is used as the recording mechanism. Here, a 488-nm $Ar^+$ laser with an output power of 16 mW is used as a light source. After passing through a computer-controlled shutter, the laser beam is focused at a point in a BSO crystal by the use of a high-numerical-aperture objective lens (Zeiss, oil immersion, NA = 1.0, 40× magnification). At the focus point, the impurities contained in the crystal absorb the light, and electrons trapped in the impurities are excited. As a result, the absorption spectrum at the illuminated point is changed compared with the nonilluminated region or background area. This situation creates the bit datum in the crystal. The light intensity on the crystal was 0.7 mW and the exposure time to record one bit was 465 ms. If the focus spot in the crystal is scanned three dimensionally, the data can be recorded in the volume of the crystal. A shutter is also controlled by the computer to turn the laser light on and off according to the sequence of the data.

Figure 2(a) shows the absorbance spectra of a BSO crystal before and after exposure to the $Ar^+$ laser

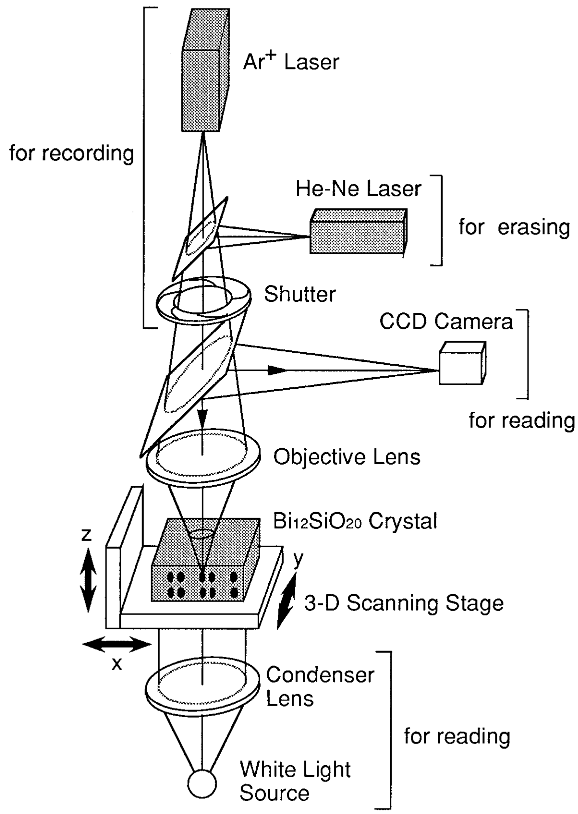


Fig. 1. Optical setup for a multilayered optical memory with a BSO crystal. An $Ar^+$ laser is used for recording bit data, and a He–Ne laser for erasing a bit datum. Recorded data is read out with a white light source.

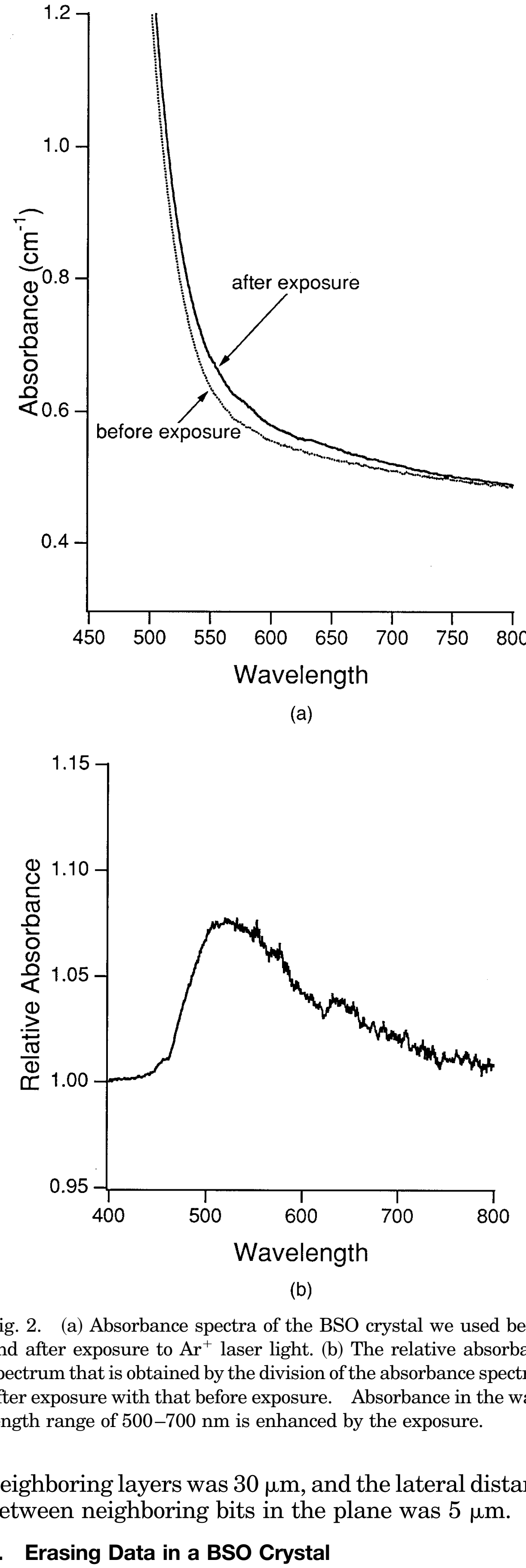


Fig. 2. (a) Absorbance spectra of the BSO crystal we used before and after exposure to $Ar^+$ laser light. (b) The relative absorbance spectrum that is obtained by the division of the absorbance spectrum after exposure with that before exposure. Absorbance in the wavelength range of 500–700 nm is enhanced by the exposure.

beam. In both spectra the absorbance for wavelengths shorter than 500 nm is increased because of the existence of Si vacancies. Absorbance in the wavelength range from 600 to 800 nm is slightly increased with exposure to the $Ar^+$ laser beam. Figure 2(b) shows the relative absorbance spectrum that is obtained when the absorption spectrum after exposure is divided by that before exposure. Clearly, absorbance in the wavelength range of 500–700 nm is enhanced by the laser-beam exposure.

To read the bit data or bit images from the crystal, the white-light illumination system and a CCD image camera, shown in Fig. 1, are used. Because the data are recorded as absorption changes in the crystal, the same objective lens is used for reading.

Figure 3 shows the experimental results of the readout data. The crystal memory in this case consisted of five layers into which the letters L, a, S, I, and E had been encoded sequentially. The dark dots in the images shown in Fig. 3 correspond to recorded bits that have higher absorption than in the unexposed region of the crystal. Cross talk, for example, in the first layer, with defocused images from other layers does not severely disturb the data readout in the first layer. Neither do the other layers suffer severely from cross talk, and every layer is well separated from the defocused images of other layers. The axial separation between neighboring layers was 30 μm, and the lateral distance between neighboring bits in the plane was 5 μm.

## 3. Erasing Data in a BSO Crystal

We succeeded in erasing a recorded bit by illumination of the crystal with red light. As seen from Fig.

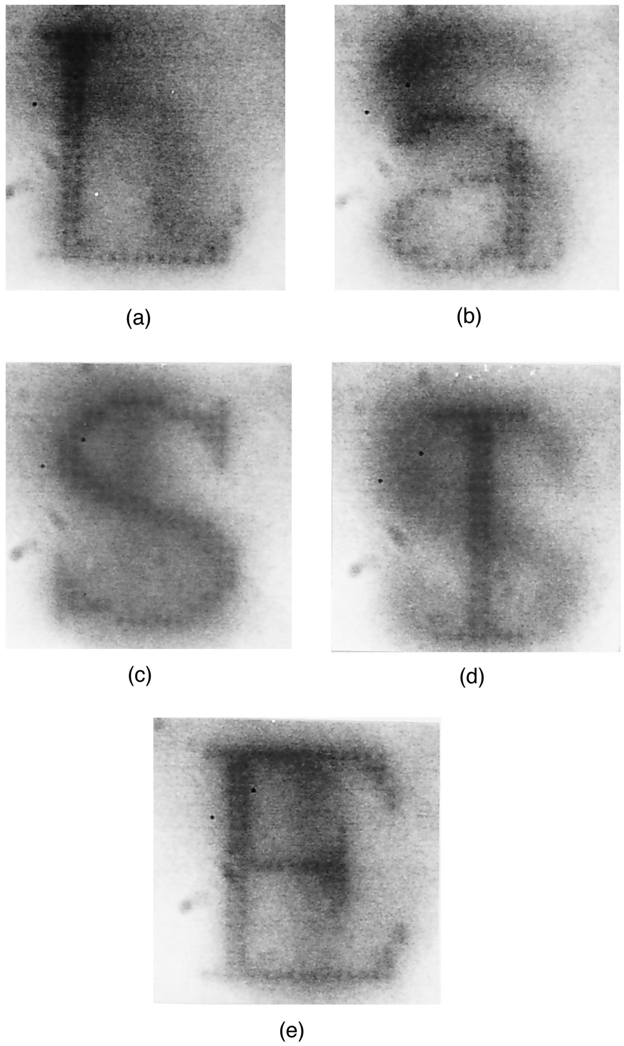


Fig. 3. Experimental results of recording and reading bit data. Five layers data were recorded. The distance between bits in the plane is 5 μm, and the distance between layers is 30 μm.

1, the optical path of the He–Ne laser beam is set to be exactly the same as that of the $Ar^+$ laser such that they focus at the same position, the focus point of the $Ar^+$ laser light. The power of the He–Ne laser on the crystal surface is 0.05 mW.

Figure 4 shows the experimental results of bit erasure. Five bits were recorded. Figure 4(a) shows the recorded data before erasure. Figure 4(b) shows the data after the He–Ne laser light irradiated the center bit of the data for 10 min. It is clearly seen that the dark dot is erased by the illumination of red light.

We have demonstrated that rewriting data at a previously erased area is possible. For this purpose, we focused $Ar^+$ laser light at the center of a square formed by the four dots and recorded a bit datum again; the results are shown in Fig. 4(c). The bit datum was successfully recorded. With this capability to optically erase and rewrite data, it is possible to produce a randomly accessible, multilayered optical memory with our system.

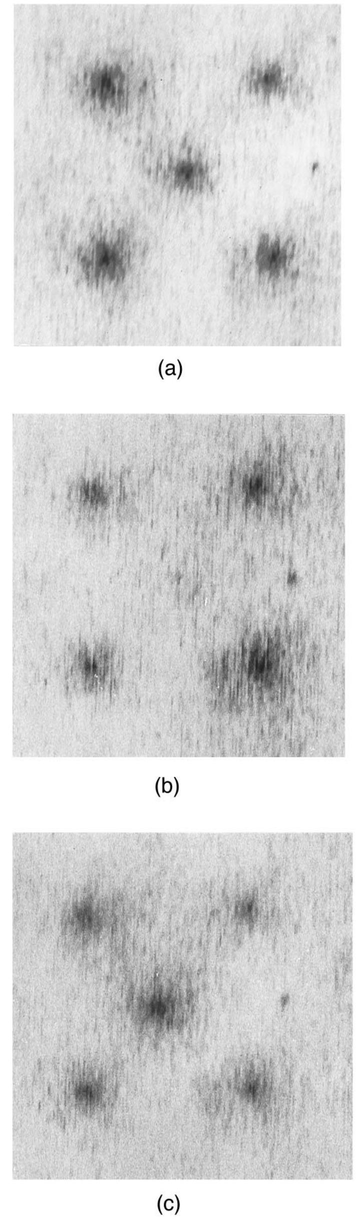


Fig. 4. Experimental results of optical erasure of a bit datum: (a) Data recorded before illumination by the He–Ne laser light. (b) The data after irradiation with the He–Ne laser beam at the position of the center bit in (a) for a few (10) minutes. The bit datum is erased. (c) A bit datum is recorded again at the center of the square formed by the four bits.

## 4. Conclusion and Discussions

We developed a read-and-write, randomly accessible, multilayered optical memory using a BSO crystal as the recording medium. In this memory, bit data were recorded as an absorption change caused by the photochromic effect of the crystal. We succeeded in recording in five layers within the crystal. Furthermore, optical erasure of recorded data was successfully carried out by simple illumination of the recorded area with He–Ne laser light. To the best of our knowledge, ours is the first demonstration of optical erasure of the photochromic effect in a BSO crystal. This result can be compared with the rather inefficient method of heating the crystal to more than 150 °C.[10–12] In view of the fact that the excitation of trapped electrons at impurity sites is involved, it is believed that the number of recording–erasure cycles could be made extremely large without the material's showing any fatigue.

We plan to perform another experiment with spectroscopic techniques to describe the erasing mechanism in detail. The optimal wavelength and optimal light power for erasure should be investigated. We expect that the erasure process will speed up by optimizing each experimental condition. It is also necessary to develop a method for nondestructive readout, namely to avoid the erasure of data during reading by the detection of a refractive-index change or polarization change of the readout beam.

We also plan to use laser-scanning confocal microscopy[3] and two-photon absorption to achieve better contrast and higher density of storage. Also, we intend to make use of the photorefractive behavior of BSO for carrying out experiments similar to those reported here.

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The e-mail address for Y. Kawata is y.kawata@ap.osaka-u.ac.jp.

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