Materials and Systems for Two Photon 3-D ROM Devices
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Abstract—The methods and systems used for storing and accessing information in three dimensions by means of two-photon absorption are described. The materials into which the information is stored are organic molecules dispersed in polymer matrices, which change structure and spectra after absorption of light. The writing and accessing of the information can be performed either bit-by-bit or in a two-dimensional (2-D) multibit plane format. Automated recording and readout three-dimensional (3-D) systems have been constructed and characterized. Channel error sources have been identified, and a custom spatial bit-error-rate test has been developed.

Index Terms—Parallel access optical memory, photochromic materials, 3-D storage, two-photon absorption, volume optical memory.

I. INTRODUCTION

The effectiveness of computers from the point of view of capacity, speed of input and output of information, power consumption, and physical space are becoming continuously more restrictive as the amount of data to be processed keeps growing exponentially. The major component which is expected to modulate the practical limits of high speed computing will most probably be the memory. In addition, because of the huge data storage requirements, the need for the parallel execution of tasks and necessity of a compact, very high capacity low cost memory is becoming essentially mandatory.

Processing the data in today’s high performance computers is to a large extent limited by data storage and retrieval rates rather than by the function of the processor. The best known and where most of the effort has been devoted for making high density three-dimensional (3-D) storage memory devices is based on holographic techniques [1]. The storage density is extremely large, especially when small angle techniques are used, with several thousands of holograms being recorded in a single crystal. Another approach to optical 3-D storage is hole-burning [2], which utilizes the inhomogeneously broadened zero phonon band as the storing medium.

Another optical method currently practiced is based on two photon processes [3], [4]. This method, which is the topic of this paper, relies on the simultaneous interaction of two photons with a nonlinear material for storing the information in any two-dimensional (2-D) area within the bulk of the memory device. Storage media, including magnetic disk, electronic RAM, and optical disks are fundamentally limited by their 2-D nature. The data capacity is proportional to the storage area divided by the minimum bit size. 3-D optical storage surmounts this limitation by extending the storage into the third dimension. They offer, therefore, an attractive possibility for highly parallel access, large storage capacity, and high bandwidth memory.

3-D memories, because they extend the storage into three dimensions, make possible the achievement of higher capacities and shorter access times [3]. Storing and retrieving the data of a complete page of several megabits simultaneously, in contrast to the single bit access, dramatically increases the usable data rate. In addition, parallel-access optical memories are to a large extent compatible with the next generation of ultra-fast parallel hybrid, opto-electronic, computers which rely on optical interconnections, and electronic processing. However, it is doubtful that a single 3-D memory system may possess all of the optimum requirements for high speed computing, therefore trade-offs between high storage density, access time, and data transfer rates need be made.

For optical memories, the density of stored information is dependent upon the reciprocal of the wavelength raised to the power of the dimension used to store information. For example, the information density which can be stored in a one-dimensional (1-D) space, i.e., tape, is proportionally \(1/\lambda\). This relationship also suggests that the information storage density is much higher for UV rather than IR light. For a 2-D memory, the maximum theoretical storage density for a 2-D storage device which uses light at 200 nm is \(2.5 \times 10^{19}\) b/cm\(^2\). In the case of a 3-D storage memory which utilizes the same wavelength of light, the maximum density which can be stored per cm\(^3\) is \(1.2 \times 10^{14}\) b/cm\(^3\). This represents an increase by a factor of \(10^5\) b/cm\(^3\).

We shall now present the principles of writing and accessing information in a 3-D volume by means of two photon absorption. Then, we will apply these principles to the storing and retrieving the information imprinted within the volume of the 3-D memory using organic materials dispersed in polymer hosts.

II. TWO-PHOTON PROCESSES

The writing process, in practice, is performed by using two laser pulses emitted by the same laser. The pulses can be either...
of the same wavelength or of two different ones, such as the fundamental and the second harmonic of a Nd:YAG laser.

It is known that intense laser beams induce multiphoton absorption which affects the population of excited states [5]. The rate of absorption depends upon the product of the intensities of the two laser pulses $I_1 \cdot I_2$. If the two photons $\omega_1$ and $\omega_2$ have the same frequency then the transition probability will depend upon the square of the intensity. It is, therefore, of considerable advantage to use ultrashort laser pulses because of their very high intensities. Note, however, that the two photons absorbed need not be of the same wavelength. All that is required is that the two photons interact simultaneously with a molecule. For two photon processes, where two pulses with the same frequency are counter-propagating pulses intersect in a nonlinear medium, the ratio of the intensities in the area of intersection to the area where the beam do not intersect is 3:1 [6]. However, by utilizing photons with carefully selected frequencies, it is possible to greatly increase this ratio. The reason for the absorption within the volume rather than the surface is due to the fact that the wavelength of each photon alone is longer, corresponding to less energy, than the energy gap between the ground state and first allowed electronic level, therefore the single photon is not absorbed. However, if two beams are used and the energy sum of the two laser photons, simultaneously interacting in the 3-D volume is equal to or larger than the energy gap of the transition then absorption will take place albeit with a much lower cross section than one photon transition. It is also important that there is no real level, only a virtual state connecting the ground and excited states, at the wavelength of either beam, therefore neither photon may be absorbed alone. When two such photons interact in a molecule within the volume, absorption occurs only at the place of pulse overlap.

III. STORING AND ACCESSING INFORMATION IN 3-D

In the case of the organic materials to be described the information is stored in the form of binary code. The two states of the binary code, 0 and 1, are formed by the photochemical changes which lead to two distinct structures of the molecular species used as the storage medium. Such an example is provided by the changes in molecular structure occurring in photochromic materials such as spirobenzopyrans after the simultaneous absorption of two photons.

To store information in a 1 cm$^2$ polymer block containing photochromic material, (see Fig. 1), we employ two photons of different wavelengths. The photon energy of each beam was smaller than the energy gap between the ground state, $S_0$, and the first allowed electronic level, $S_1$. Each light beam propagates though the medium without any observable absorption. When the two beams intersect at a preselected point within the memory volume and their effective excitation energy is equal to the sum of the two photon energies $E_1 + E_2$, absorption will occur if the $E_{S_1} - E_{S_0}$ energy gap is equal to or smaller than $E_1 + E_2$. At the point where the two beams interact, the absorption induces a physical and/or a chemical change which distinguishes this excited microvolume from any other molecules in the memory bulk which have not been excited. The two molecular structures now present, i.e., the original and the one created by the two photon absorption, become in practice the “write” and “read” forms of a 3-D optical storage memory. For the successful completion of this type of writing and reading, the light beams which perform either function must also be capable of traversing the medium and be absorbed only at preselected areas within the memory volume where the two beams intersect.

At the present time we believe that storing and reading information in a 1-in diameter, half inch thick cylinder is possible. The procedure used to access the information written within the volume of the memory is similar to the store process except that the “reading” form absorbs at longer wavelengths than the “write” form. Therefore one or both laser beam wavelengths must also be longer than the ones used for writing. Under these conditions reading is achieved with wavelengths longer than writing, therefore no writing takes place while reading. After the written molecule is excited it emits fluorescence. The fluorescence spectrum is located at longer wavelengths than the absorption of both the write and read forms. The emission is detected by a photodiode or charge coupled device (CCD) and is processed as 1 in the binary code. The proper selection of materials which provide widely separated spectra is extremely important because it assures that only the “written” molecules emit light and only from the area of the written memory that is being excited.

Erasing the information may be achieved either by increasing the temperature of the memory device to $\sim$50 °C or via irradiation at a specific wavelength other than that for writing or reading. By raising the temperature, the “written” molecules are raised above the energy barrier separating the “write” and “read” forms causing the written molecules to revert to the original form. The information is thus erased and the 3-D memory is ready for storing new data. A limitation of “erasure” by temperature is that it does not selectively “erase” specific bits of the information stored in the 3-D memory volume.

Fig. 1. Writing and reading information in 3-D by two-photon process. Upper: two-color laser beam intersection within the memory volume; lower: energy level diagram of two-photon process.
However, utilization of light for erasing circumvents this difficulty and makes it possible to erase specific, preselected bits of information, without affecting any other places within the memory.

IV. PHOTOCROMIC MATERIALS FOR 3-D MEMORY

There is a large number of materials which change their molecular structure and spectroscopic properties after illuminated with light [7], [8]. Two distinct forms of those materials may potentially represent the binary codes in optical memories. However, to be suitable for application in the 3-D memory devices described in this paper, the materials should possess certain characteristics, which strongly limits the number of possible candidates:

1) high two-photon absorption cross section to perform efficient writing of information;
2) high efficiency of photochemical process;
3) the written form should emit fluorescence with high quantum yield;
4) both write and read forms of the material must be stable at room temperature;
5) high fatigue resistance to perform more than $10^5$ write-read-erase cycles;
6) wide absorption and emission spectra separation to minimize the crosstalk between the written bits;
7) capability for nondestructable readout process.

To our knowledge, at the present time, there is no “ideal single molecule” which satisfies all of these requirements. However, a number of materials may be used with some success for optical storage and access of information.

Spiropyans are a rather important class of photochromic molecules [7]–[9] which can be used as 3-D storage materials [3], [10]. The chemical structure of these molecules and their photochemical mechanism are shown in Fig. 2. Spiropyans are usually colorless in one form because they are composed of two $\pi$-electron moieties situated orthogonal to each other. Therefore the spectrum of this molecule consists of the two individual spectra without the long wavelength absorption band which is indicative of the planar, completely conjugated molecular structure. Upon excitation of the close form A, bond cleavage and rotation of the moieties take place making possible the formation of a nearly planar conjugated structure, referred to as the merocyanine form, B. The $\pi$-electron system extends, now, throughout the molecule which is responsible for the red shift observed in the absorption spectrum of this form, from the ultraviolet to the 500–600 nm region.

The spiropyran and the other photochromic materials discussed in this paper, were dissolved in a monomer, i.e., methyl methacrylate (MMA), at small concentrations such as $10^{-5}$ M. A very small amount of radical initiator was added to the MMA/photochrome molecule solution and then allowed to polymerize at a slow rate. Examination of the polymer/photochrome bulk, by means of light scattering, reveal that the matrix was homogenious and cluster formation was insignificant, at least of clusters with sizes large enough to induce either unusualy intense fluorescence at some written areas or generate some larger written spots than the norm. We estimate that if clusters were formed their size was smaller than 0.2 $\mu$m.

Because of their large spectral shift between the original and merocyanine forms and the fluorescence of the latter, these molecules were found to be quite promising as storing media for 3-D optical memory devices.

Another type of molecular transformation which may be used in electronic devices is light induced dimer-monomer transformation, as shown schematically in Fig. 3. The process of reversible photodimerization and photodissociation of polycyclic aromatic hydrocarbons such as anthracene and its derivatives [11]–[13] may be used for developing photochromic materials for optical memory devices. The photodimers are formed by excitation of the corresponding monomers to the first singlet excited state and subsequent interaction of two monomers. The quantum efficiency of this process is found to be independent of the excitation light wavelength.

When the photodimers are excited they dissociate adiabatically via intermediate excimer formation [13]. The dissociation of the dimer results in the regeneration of a conjugated double bond system and consequently a red shift of the absorption band of the dimer. The monomer has its long wavelength absorption band in the 300–400 nm region, while the dimer is blue shifted and has practically no absorption at wavelengths longer than 300 nm. The monomer was found to emit with a fluorescence quantum efficiency of approximately 30%, while the dimers are practically void of any fluorescence. The fluorescence spectrum of anthracene dispersed in PMMA is between 380–450 nm.

The photodissociation and photodimerization processes, in the absence of oxygen, are very efficient in both the forward and reverse reactions, which suggests that the storing and accessing information processes can be repeated efficiently many times.

In the dimer/monomer molecular system, the dimer species which corresponds to the binary “0” state absorbs in the ultraviolet and upon two-photon excitation is transformed to the monomer, which becomes the binary “1” state. The
information is accessed by the fluorescence emitted when the monomer is excited. When two 532 nm beams intersect in a volume, containing anthracene dimers, (binary “0” state), the dimer molecules located within the volume where the two beams intersect are excited by a two photon process and then the excited dimers photodissociate to form monomers, binary “1” state. Accessing the stored information is achieved by illumination of an entire written 2-D page with low intensity 355 nm plane beam which induces fluorescence by one photon process.

One advantage of the dimer-monomer based 3-D storage systems is that, unlike the spiroyrans, where the written state reverts spontaneously, within a few hours at room temperature, into the unwritten state and consequently the information previously stored is erased. Both dimer and monomer forms are highly stable at room temperature. In addition, the high absorption cross-section and high quantum efficiency of fluorescence suggest that this molecular system is very suitable for utilization in 3-D memory optical devices.

V. Organic Dye ROM Material

A new memory material was designed by us lately for 3-D memory ROM devices, where the information is written once, stored indefinitely, but may be retrieved for very large number of times. It is composed of an organic dye which has different structures when dispersed in acidic or basic host media. For example organic laser dyes, such as Rhodamine B, can exist in two forms, depending on the acidity and polarity of the matrix or solvent. One of these forms, Rhodamine B base, is colorless and has no detectable fluorescence. However, in the presence of acid, this colorless form undergoes a transformation into a colored, strongly fluorescing dye, Rhodamine B, which is well known as a stable and efficient laser dye. This process is shown schematically in Fig. 4.

Using molecules which have these properties we have developed new optical storage materials which are composed of two components.

1) The first component is a molecule which when excited to its first allowed electronic state is converted into an acid (referred to as acid generator).

2) The second component is an organic dye precursor, which reacts with the photogenerated acid to form a room temperature stable, strongly fluorescing dye.

The unwritten form, binary “0” state, of this memory material is the mixture of the acid generator and the dye precursor. The written form is the fluorescing dye material which is the product of the chemical reaction that takes place after photoactivation.

A variety of dye precursors and acid generators [14]–[17] exist. However, to be suitable for use with two-photon 3-D memory devices these molecules must possess the following characteristics:

1) the photoprocesses which generates the acid must have a high quantum efficiency;

2) both the write and read forms of the 3-D material should have a long term, years, stability at room temperature;

3) the written form should be a light stable, strongly fluorescing dye that can sustain its fluorescence efficiency without degradation for at least 10⁶ reading cycles;

4) the material should be highly soluble in monomers and the corresponding polymer hosts;

5) the absorption spectrum of the acid generator should have high absorption cross section in the 355 nm region or another easily accessible two photon wavelength.

For example, the 1064 and 532 nm (SHG) pulses from Nd:YAG laser, which are the wavelengths that we currently employ for 3-D volume writing.

The new ROM material, which we describe here, possesses all of the above properties and therefore we have been able to utilize it successfully in 3-D memory devices. We have studied the detailed kinetics, mechanism and spectroscopic characteristics of this new ROM material which will be published elsewhere. Here we describe briefly only the steps which are important for the operation of the memory device.

We have used 1-nitro-2-naphthaldehyde (NNA) as the acid generator component which upon excitation with UV light undergoes phototransformation into the corresponding nitroso acid, as shown in Fig. 5. The quantum efficiency of this photoreaction was measured to be 50% and we found that it did not depend on either excitation wavelength or polarity of the host medium.

Rhodamine B base was the dye precursor, which we found to react with the photogenerated nitroso-acid to form the colored Rhodamine B dye. Fig. 6 shows the absorption spectra of NNA and Rhodamine B base and their maxima which are located below 400 nm. The described ROM material was composed of NNA as an acid generator and Rhodamine B base as a dye precursor dispersed in solid PMMA matrices. After excitation with 355 nm light, the composite develops a deep pink color and a bright red fluorescence was emitted from this form when the material was illuminated with 532 nm light. The absorption and fluorescence spectra of the light induced written form are also shown in Fig. 6. In the case of solid matrices, both the unexposed and colored areas, unwritten and written areas, of the polymer film or block did not show any spectral changes or degradation at room temperature when stored in the dark.
When a solution of NNA was irradiated with a 355 nm picosecond laser pulse, the formation of a fast transient species was observed. The rate of formation of this, the only intermediate observed in our kinetics experiments, was practically as fast as the excitation pulse duration, $\tau_{\text{pulse}} \sim 30$ ps. The accumulation rate constant value was measured to be $2 \times 10^{10}$ s$^{-1}$ and it decays to the written form in a few nanoseconds. This fast reaction rate coupled with the high quantum yield of transformation to the written form and the very intense fluorescence of the written microvolume suggest that this molecular system is suitable for utilization in 3-D memory devices.

We have successfully utilized this polymer based light sensitive molecular system as a ROM memory material for our 3-D optical memory system to store many 2-D planes inside the 3-D volume of the memory. Other photochromic materials have been studied in our laboratories and show promise for use as optical memory devices.

The 3-D materials and devices presented here have been tested for fatigue under various parameters, i.e., temperature and light intensity and energies. It was shown that at reading light energies less than 4 mJ/cm$^2$ more than $10^6$ reading cycles were able to be performed at room temperature without noticeable degradation. The material can be stored in ambient light as long as there is no 355 nm UV light.

VI. 3-D MEMORY SYSTEM CHARACTERISTICS

Two-photon 3-D memories are similar to the multilayer optical disk systems with the potential for simple media fabrication, many layers, parallel access for high data transfer rates, and low raw bit error rates (BER). Orthogonal intersection of the writing beams may be used, or if ultra-short (e.g., <100 femtoseconds) pulses are used, a counter-propagating arrangement [4], [18] is feasible. While single bits may be stored and recalled, parallel access of lines or planes of data is naturally accommodated in two-photon 3-D memories, to provide increased data transfer rates. Due to diffraction of the addressing beam as it propagates across the data image, there exists a tradeoff between the volumetric density of the memory and the parallelism, or data transfer rate. We have performed a variety of 3-D memory experiments to demonstrate writing, reading, and erasure, and recently we have begun system-level characterization experiments to evaluate this technology’s practical potential [19]–[22]. The progression of this evaluation has proceeded from the demonstration of multilayer recording of “noisy” images, to the qualitative improvement of those images to the point at which more quantitative techniques are needed to measure the performance of the media, recording, and reading systems.

A. Experimental Removable Media Storage System

We have constructed an automated recorder shown schematically in Fig. 7, which is used to store data in $10 \times 10 \times 10$ mm$^3$ samples. These cubes are fabricated by incorporating a desired concentration of active molecules in liquid MMA, polymerizing the solution, and cutting and polishing the cubes. Chrome or Ektagraphic film masks are illuminated by 1064 nm, 35 ps pulses from a mode-locked Nd:YAG laser and imaged into the media to form 4 mm × 4 mm data planes. The 532 nm frequency doubled beam from the laser is anamorphically focused to a 80 \( \mu \)m sheet and spatially and temporally aligned with the IR image plane within the memory cube. Approximately 2400 pulses at energy fluences of 300 mJ/cm$^2$ are used to saturate the recording. The memory, mask, and imaging lens closest to the memory were mounted on motor driven linear stages. Custom LabView software controls the exposure timing of the laser shutter, the mask stages to select individual data patterns, the memory cube stage to position the cube relative to the addressing beam, and
the imaging lens stage for automatically adjusting the focus at different planes in the memory.

Retrieval and analysis of the data is performed with approximately 200 µW of CW illumination at 543 nm from a HeNe laser introduced along the green path of the recorder. The induced fluorescence is imaged onto a cooled CCD camera (Princeton Instruments, 1316 × 1035 pixels, 12 b dynamic range) and analyzed with custom made software to perform the bit threshold decisions and calculate average signal separations and spatial bit-error-rates. Retrieval of images from the memory has also been demonstrated in the portable ROM systems shown in Fig. 8. Both systems use a simple stepper motor driven stage, a 200 µW HeNe laser, and a low cost video camera.

B. Signal to Noise Ratio Considerations

We are currently investigating the spatial signal-to-noise ratio (SNR) obtained for each data plane upon readout, which is dependent on the variation of the individual bit’s signal levels. The absolute signal strength is determined by the media doping concentration, and two-photon recording level, as well as the readout laser power, media fluorescence efficiency, and the detector collection efficiency and integration time. Signal variations are introduced by deterministic effects such as the nonuniform profile of the Nd:YAG laser mode, nonuniformities in the mask (or eventually the spatial light modulator) and detector array, background writing from 2-photon writing by the green addressing beam, and nonuniformities introduced into the addressing beam by absorption as it propagates through the media. Most of the crosstalk mechanisms are also deterministic, including optical system resolution and aberration effects, diffraction and misalignment of the addressing beam to adjacent planes during recording and readout, and misalignment of the detector pixels with respect to the data plane bit-images. For example, the variation of recorded spot size across a data page due to diffraction and aberration effects can be accurately modeled and is relatively constant from page to page. Thus the intra- and inter-page crosstalk components due to the aberration-induced spreading of spot energy may be compensated by straightforward spatial equalization techniques [23]. Finally, there are random errors introduced by defects in the media, and by scattering of the beams by internal and surface defects/dust, and potentially by the recorded bits (due to the small index modulation at each bit, this effect is thought to be very small).

C. Bit Error Rate Evaluation

To characterize the causes of spatially varying optical signal separation (spatial noise) within our data planes, we are developing a 2-D spatial bit-error-rate test stand. Ultimately, these data planes will be read at high rates, thus the effects of temporally varying signal levels must also be analyzed. The construction of a temporal BER test stand for temporal noise analysis in this memory will be especially demanding due to the potentially large number of parallel channels operating simultaneously at high data rates. The tools needed for this analysis include automated recording facilities to record enough images to generate accurate error statistics, an automated readout and data collection system, and static (spatial) and dynamic (temporal) 2-D data analysis software to identify bit boundaries and signal levels and extract the signal and noise statistics.

Currently, the 2-D spatial BER test stand uses the automated recorder stages for recalling data planes, and the CCD camera and custom MatLab software for analysis. Automated alignment of the data plane image and the CCD pixel grid results in no more than one pixel offset errors (each bit is sampled by more than one pixel), after which the code optimizes
the thresholding, compares the recorded bits to the input bit pattern, and identifies the bits that are in error. If no bits are in error, we may estimate the BER by examining the variations in signal level for the one and zero bits, and calculating a “signal separation to static noise ratio (SNR).” This estimated, of “soft” BER, is also useful even in the presence of “hard” bit errors, since many of the bit errors we currently see are due to material impurities, and polishing scratches that will be eliminated in the future by improved fabrication techniques (e.g., clean room preparation, injection molding, etc.). The soft BER results thus provide an estimate of the static error characteristics potentially achievable with this technology. The SNR for each data plane is calculated as the average signal separation divided by the rms standard deviation of the 1’s and 0’s, since the distribution of these levels is, in general, different for the 1’s (bright bits) and the 0’s (dark bits), as below

$$\text{SNR} = \frac{\mu_1 - \mu_0}{\sqrt{\sigma_0^2 + \sigma_1^2}}.$$  

To estimate the BER, Gaussian probability density functions are fitted to the signal level histograms. Fig. 9 shows the user interface of the test set.

D. Data Normalization Techniques

The primary factor affecting SNR is the poor mode quality of the IR beam (from a flashlamp-pumped Nd:YAG laser) illuminating the mask. Since the depth of modulation (and resultant fluorescence upon readout) of the stored image is proportional to the product of the data mask transmittance and the profile of the laser beam (neglecting the effects of addressing beam uniformity), we can theoretically remove the effects of the infrared image-bearing beam’s mode by dividing the data plane images by recorded laser mode reference image(s). To separate the media induced effects from these laser-mode effect, we have directly analyzed the image of the laser illuminated mask. We see similar SNR’s for mask images captured directly into the CCD camera and the mask
Fig. 11. Results of 100 data layer recording: (a) side-view of the recorded layers and (b) image of one data plane.
images recorded into the media and subsequently readout to the camera. Diode-pumped solid state picosecond lasers will shortly be commercially available, and their use should ameliorate this effect, but one immediate solution is to apply a spatially variant thresholding or renormalization technique [24].

Since the effect of the laser mode is deterministic repeatable, we can record an image of the laser mode along with the layers of data planes, and use it to normalize the signal levels during readout, in a manner similar to the normalization and synchronization bits recorded in the data streams in conventional optical disk storage. Testing this technique by normalizing illuminated mask images without recording them into the media has resulted in SNR’s as large as 22:1.

To test the usefulness of this technique for a series of recorded data planes, ten planes of 30 × 30 random bit patterns were recorded in the ROM media. A plane containing a pattern of all 1’s was also recorded to provide the pixel-by-pixel signal variation due to the laser mode. These pixel values were then used to normalize the data plane pixels prior to thresholding. This initial test used a large bit size of 120 μm by 120 μm by 80 μm and an inter-plane pitch of 400 μm. Without normalization, there were 341 total errors, the average SNR was 3.26, and the estimated BER was 3.9 × 10⁻².

One of the normalized data plane images is shown in Fig. 10, along with a histogram of the data plane, and a plot showing the variation of BER over various 6 × 6 b regions of the data plane. For the 9000 b recorded in the 10 planes, normalization using the laser mode image lowers the number of erroneous bit decisions to only two, and provides an average SNR of 8.34, and an estimated (based on Gaussian fits to the histogram statistics) BER of 2.4 × 10⁻⁶.

Ideally, this technique would have produced SNR’s comparable to that of chrome masks directly imaged onto the CCD array (SNR ~22:1). The difference arises due to the noise generated by the process of division by the laser mode image. If the laser mode and data images are not precisely aligned with respect to one another (due to mechanical-stage walkoff in the recording or readout process), or if the images differ due to random defects or scratches, division of the data pixels by reference pixels with values close to zero may result, amplifying the effect of the displacement or defect error. Another major source of errors is misalignment of the bit-images with respect to the CCD pixels, which results in significant intersymbol interference. The effect of pixel-bit misalignment may be removed by either recording blank “guard-bands” around each bit, or by simply undersampling the recorded bit [25]. For this data, the central 25% of each bit was sampled, as this was empirically determined to provide the best (SNR) tradeoff between absolute signal strength and noise generated by the process of division by the laser mode [25].

These displacements and defects, while removing the effects of the poor laser mode. In a recent experiment, 1 Mb of data was stored the ROM cube media in the form of 100 data planes having 10⁷ random bits/plane [22]. As shown in Fig. 11, the planes were recorded on an 80 μm pitch. A localized autogain and thresholding algorithm (using data from 3 × 3 b regions centered on the bit to be thresholded) was implemented to remove the effects of the laser mode nonuniformity, and each bit was under-sampled as before. This resulted in 493 errors out of 960 400 measured bits, mostly due to small scratches and dust particles on the cube surface. The average SNR for the 100 planes (after the autogain and thresholding) was 8.08:1, with local SNR’s (over 10 × 10 b regions) of greater than 19:1 measured within individual data planes, indicating the potential impact of sample fabrication improvements. The SNR of 19:1 corresponds to a BER of less than 9 × 10⁻¹³. We believe that we can store 1000 planes with 10⁷ bits per plane.

VII. CONCLUSION

We have shown that by utilizing virtual transition nonlinear absorption processes we have been able to write and read information in 3-D space. We have described the optical and spectroscopic properties several photochromic molecules which demonstrate their capability for storing and displaying information at nanoseconds speeds. Parallel processing of the data in the form of 2-D bit planes has been achieved. Automated recording, replay, and analysis systems for page oriented 2-photon data storage have been constructed and characterized. Portable ROM systems have also been assembled and tested. Experiments in ROM media using these facilities have demonstrated storage of 1 Mb in 100 planes on 80 μm pitch, with a lateral bit size of 30 × 30 μm². Scratches and dust on the cube media used in the 100 plane experiment resulted in 493 errors out of 960 400 measured bits, however, BER estimates based on data histograms indicate the potential for error rates of less than 10⁻¹².

Even though there are several limitations to the materials and system presently employed, there is strong evidence to suggest that the practical application of two photon 3-D memory devices is feasible.

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REFERENCES

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In the Photonic Switching Department at AT&T Bell Laboratories, he investigated free-space optical interconnections (FSOI) for photonic switching and optical computing, using nonlinear Fabry–Perot etalons and Symmetric-Self-Electro-optic Effect Devices. His research included optical system design and packaging for free-space optical systems using FET-SEED “smart pixel” processing arrays. In the course of that work, he designed, constructed, and tested six prototype FSOI switching systems. Since joining the faculty of the University of California and the staff of Call/Recall, Inc. in 1994, he has been involved in the design and testing of optically interconnected 3-D computer systems as well as the characterization of 2-photon 3-D memory materials and the design of 3-D optical read/write heads and systems for these materials. This work has demonstrated 100 data layer 3-D recording and two portable ROM systems using this 2-photon media. He holds seven patents, has published over 80 journal and conference papers, and four book chapters.

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Dr. Esener received the Certificate of Recognition from NASA in March 1997 for his work on optically addressed RAM. He is a member of OSA and SPIE and a Co-Founder and President of Call/Recall Corporation.

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Dr. Rentzepis has received several awards in chemistry and physics and is a member of several scientific societies and academies.