Multiplexed Holographic Data Storage in
Bacteriorhodopsin

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Summary of Technical Accomplishments

Biochrome photosensitive films in particular Bacteriorhodopsin exhibit features which make these materials an attractive recording medium for optical data storage and processing. Bacteriorhodopsin films find numerous applications in a wide range of optical data processing applications; however the short-term memory characteristics of BR limits their applications for holographic data storage. The life-time of the BR can be extended using cryogenic temperatures [1], although this method makes the system overly complicated and unstable. Longer life-times can be provided in one modification of BR - the “blue” membrane BR [2], however currently available films are characterized by both low diffraction efficiency and difficulties in providing photoreversible recording. In addition, as a dynamic recording material, the BR requires different wavelengths for recording and reconstructing of optical data in order to prevent the information erasure during its readout. This fact also put constraints on a BR-based Optical Memory, due to information loss in holographic memory systems employing the two-lambda technique for reading-writing thick multiplexed holograms [3].

Thus, we concentrated our efforts on the solution of the following problems:

1. Investigate volume holograms recording and reconstruction in 2-λ geometry in the general case when reference and readout waves are highly divergent spherical beams.
2. Experimentally performed multiplexed holograms recording using available short life-time BR films in order to verify our theoretical model.
3. Developed the means to circumvent the limitation on the optical storage density peculiar to the Holographic Memory systems exploiting the 2-λ technique.
4. Investigated hologram recording regimes using long life-time states of the BR.
5. Investigated features of the BR for achieving nonvolatile readout of the stored information.
6. Investigated applications of the BR in the system supporting Optical Memory modules (SLM, optical interconnection, etc.)

We devised a simplified analysis/calculation scheme for calculating critical parameters of the holographic memory system employing highly divergent reference/readout beams and different wavelengths for data recording and reconstruction [1,2]. Such parameters as relative intensity distribution and (spatially variant) spatial resolution in the reconstructed image as well as and optimal geometric parameters for the read/write setups were derived. In addition, the selectivity of the system and cross-talk between multiplexed holographic images were estimated, and shown to be in agreement with experimental results [3].

1. We showed that information loss peculiar to the two-lambda hologram read/write technique can be circumvented using a multilayer recording medium [4]. We demonstrated theoretically and experimentally that such a system allows one to
significantly increase the storage density of the holographic memory without
decreasing diffraction efficiency and/or increasing access time as compared to
competing two-lambda systems.

2. We experimentally demonstrated multiplexed hologram recording in purple
membrane BR-films, which until now (to our knowledge) has not been employed in a
holographic memory system due to short life-time [2,3]. We showed that the
properties of purple membrane BR-films admit two regimes of hologram
multiplexing:

I. The hologram recording regime providing both long storage time (~5h) and low
sensitivity (3-4J/cm\(^2\)) on the wavelength \(\lambda=633\text{nm}\) using for reading-out [3, 5].

The high sensitivity of the readout beam allows one to significantly increase the number
independent accesses in optical memory systems without destroying stored information.
Calculation shows that multiplexing 100 holograms per spot (2x2mm\(^2\)) (0.1 Gbit) in such
a regime allows \(10^4\) readout operations (100 readouts of each hologram) with a decrease
in DE of only 50%. This feature, along with the high value of the storage time, allows
one to consider currently available purple membrane BR-film as an alternative recording
material for constructing, e.g., cache-type memory systems.

II. Multiplexed holograms recorded in parallel and their selective reconstruction in real-
time[2, 3].

This approach incorporates the modification of both angular and shift-multiplexing
hologram encoding techniques along with an incremental exposure regime [4,5].
Holograms were recorded using an M-type recording regime of the BR. We
experimentally demonstrated that by use of this technique one can circumvent the
problems related to both short life-time of the M-state (2 min. for our films) and erasure
of the holographic information during its readout. Thus, we were able to verify
experimentally the calculated parameters of the optical memory using the short life-time
M-state of the BR.

4. We considered the application of the BR (in particular multiplexed holograms
recording in the BR) also for optical data processing.

- We demonstrated theoretically and experimentally that multiplexed holograms
recorded in parallel can be used as an interconnection pattern reconfigurable in
real-time. We presented the basic principles of such interconnections and
estimated some of its parameters [3, 5].

- We showed that the technique of holographic parallel recording [2] can also be
used for multichannel processing of optical signals allowing for significant
increase of data throughput in pattern recognition systems [2].

- We demonstrated that the M-type hologram recording regime in the BR can be
effectively used for constructing an optically addressable SLM [6]. This grating-
type SLM is characterized by the following features:

  - high contrast
  - high sensitivity
  - a flexible transformation regime for optical signals which can be varied by
    changing the SLM parameters(relative intensities of the beams forming the
    active area of the SLM) to provide:

    - either a linear regime(for transformation of both binary and gray-
scale optical signals);
Informal Report of Significant Findings

submitted to Charles Gary, Program Monitor, October 1998
Nondestructive readout of the holograms recorded in a Bacteriorhodopsin

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October 21, 1998

We carried out two experiments examining the possibility of attaining non-volatile reconstruction of holograms recorded in purple-membrane BR-films.

The first approach is based on the idea that the quantum yield of phototransitions in BR depends on relative orientation of BR molecules and polarization of the light which launches the photocycle in BR. If this dependence is significant, then one can suppose that the hologram recorded in oriented BR-films can be reconstructed at the same wavelength without erasure using appropriate polarization of the readout beam. The experiment supporting this assumption was carried out using the setup depicted in the following figure:

We project the blue image on the surface of BR-film constantly illuminated by red light and observe the modulation of the red light at different relative polarization orientations of the blue and red beams. To enhance the modulation contrast we employ a Mach-Zender interferometer geometry (see the figure) allowing us to subtract the 0-order component of the readout red beam and observe only its modulated part.

The images observed in these two polarization cases are presented in the next figure:

The difference between the image contrast was estimated to be as high as 5 times, and cannot be explained by induced anisotropy of the BR. If we assume that the modulation takes place in the M-type regime, then the most probable explanation is that red light selectively excites the BR...
molecules having the appropriate orientation, and the back transitions of those excited BR molecules depends on the blue light polarization. The explanation of the low contrast image observed at orthogonal polarization can possibly be attributed to an alternative process where the blue light excites other BR molecules not previously excited out of the base state.

The investigation of the holograms recorded in BR in its initial state by blue light led us to results showing that the process cannot be considered as an M-type hologram recording. A hologram was recorded by blue and reconstructed by red light. We found that holograms recorded by only blue light and then reconstructed by red light have a lifetime around 5 hours and very low sensitivity relative to red readout light (~3J). Illumination by the red light (readout process) brings the BR to the state where only the M-type regime predominates. The initial BR-state (i.e. erasure to ready the BR for new recording by blue light) is recovered by spontaneous decay in about two days, or by exposing to light with 380-400nm wavelength. In the following table we compare the parameters of holograms recorded by blue light before and after readout by the red light.

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Rec. by blue light (λ&lt;488nm)</th>
<th>Rec. by red light (λ=633nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2min</td>
<td>0.1mJ</td>
<td>4 - 8%*</td>
</tr>
</tbody>
</table>

* Varies with type of purple membrane film used.

The mechanism of this recording regime is not yet clear - apparently this is a Q-type regime which exhibits a behavior somewhat different from that described in the literature.

We are continuing the investigations, but even now the results are thought to make purple membrane BR-film an alternative material for constructing, e.g., cache-type memory systems. The figures in the table indicate that such a recording regime can provide a significant number of independent accesses in optical memory systems without destroying stored information. Calculation shows that multiplexing 100 holograms per spot (2x2mm²) (0.1 Gbit) in such a regime allows 1000 readout operations with a decrease in DE of only 50%.
White Paper - submitted to NASA-Ames

August 10, 1998
BRIEF SUMMARY OF PROGRESS OVER THE LAST YEAR:

1.) We devised a simplified analysis/calculation scheme, based on coupled mode theory, for calculating critical parameters of our two-lambda holographic memory system. Our system[1], which used highly divergent spherical beams (via optical fibers) for both the reference and readout beams. Such parameters as relative intensity distribution, (spatially variant) spatial resolution, optimal parameters for the readout beam, and optimal geometric parameters for the reconstruction beam were derived. In addition, cross-talk between successive multiplexed holographic images was estimated, and shown to be in agreement with experimental results.

2.) We estimated the storage density achievable with BR-based holographic memory employing the aforementioned two-lambda technique, and suggested yet another multi-layer architecture[2] to allow an increase in storage density. We showed that this method afforded several advantages over rival methods, such as: (a.) increased selectivity without the partial loss of information inherent to two-lambda geometries, (b.) increased diffraction efficiency, and (c.) decreased access time.

3.) We investigated a hologram multiplexing technique employing both incremental recording and shift multiplexing, and showed that this hybrid approach allows one to multiplex (in parallel) a number of holograms within the same physical volume of the BR medium. We experimentally demonstrated that by use of this parallel recording technique the following optical BR-based memory systems can be realized:
   - Short-life-time BR films (purple membrane) can be used for holographic multiplexing. We recorded (10) holograms (each containing 1Mbit of information) in the same 0.01 square inch spot of the BR film, and selectively reconstructed all information contained in each hologram (using the two-lambda approach). The recording rate was 10Mbits/sec. Extrapolating on these parameters, we estimate a 36Gbit data capacity on a 6 x 6 inch BR disk.
   - The parallel multiplexing of point-source beams can provide the adaptive interconnection between 2-D arrays of lasers and photo-detectors (e.g. optical crossbar switches and multi-channel processing of optical signals).

4.) We experimentally demonstrated that the scattering noise of the BR, which limits the number of spatially overlapping holograms, can be significantly suppressed using filtering holograms, while having no detrimental effect on the reconstructed images.

PROPOSED FUTURE WORK

The previous results, along with the results of other preliminary experiments, lead us to suggest the following approaches (for future research) for significantly improving the performance of BR-based holographic memories.

1.) First, we plan on increasing the number of holograms that can be recorded within the same physical volume of the BR film (as mentioned above, we can currently record 10 holograms per
spot) and investigate the maximal attainable storage density in the BR-based optical modules. Our preliminary experiments showed the possibility of multiplexing 100 holograms per 2.5 x 2.5 (mm$^2$) spot on 100 micron thick BR film (using a 100ms exposure time), to attain 0.5 Tbit capacity for a 6 in. x 6 in. x 100 micron recording area.

In order to increase storage density, we would concentrate our effort in two directions:
- We would continue our investigation of the incremental recording technique. In particular, for recording 100 holograms in parallel it is necessary to significantly increase (temporal) switching frequencies between reference beams (we currently use an array of fiber-optic based reference beams) using, e.g., a scanning mirror or an acousto-optic deflector.
- Reduce bit error rate during detection of weak signals by use of holographic filters to reject noise (see Fig. 1). We would investigate use of such filtering for a variety of recording geometries and recording materials.

2.) The properties of BR allow us to directly amplify weak optical signals. This feature could be exploited for the purpose of increasing the number of spatially overlapping multiplexed holograms (this increasing storage density). One of the possible approaches is based on the high spatial resolution of BR, and the fact that the state transition time is finite (~50 microseconds). Since absorption and refractive index varies significantly with states (e.g. between the M and BR states), the BR film can be exploited to act as a "trigger". First, we can increase the intensity of the image being detected using scale compression, i.e., demagnifying the image increases the intensity). The high spatial resolution of BR-films allows us to increase the intensity by at least an order of magnitude. Then, let us assume that a BR-film is continuously illuminated by a red light, which holds it in the excited M state. A (weak) reconstructed image, propagating on a blue light, is projected on the BR film surface, locally initiating the M $\rightarrow$ BR photo-induced transition. Simultaneously, the red light pushes BR molecules back to the excited M state. Naturally, the state transitions reach a steady state equilibrium, but the blue light image spatially modulates the BR film, also spatially modulating the (stronger) red light that ultimately is transmitted through the BR film. The red light, which now carries the (strengthened) image, can now be detected (in negative contrast) using, e.g., a CCD camera. Experimental results demonstrate the ability to detect weak optical signals in this manner.

An alternative approach is to "pump" the BR film with blue light, and modulate the BR with the image cast onto the BR surface using red light. In this case, we again obtain amplification, although the (amplified) output image (now with positive contrast) is now formed from the transmitted blue light. Experimental results show that this approach generally gives improved contrast ratio. However, disadvantages include the fact that silicon CCD detectors are generally less responsive to blue light than to red. In addition there are additional problems associated with the fact that some of the "intermediate" BR states are also photo-reversible.

In both cases, we employ the optical subtraction of the non-modulated part of the readout beam to increase image contrast. The amplification effect that we have observed could be enhanced significantly by the availability of thin films (~5 microns) having higher density of BR molecules.

3.) Normally, holographic memory systems simultaneously employ multiple read/write setups (for each layer), in order to enhance storage density (Figure 2a). This results in prohibitive cost and bulkiness of the system (e.g. requiring multiple SLMs, and/or CCDs etc.).

In order to reduce the cost of the system and make it more compact, we propose a waveguide access scheme for reading and writing to a multilayer disk, that will use a common read-write access setup for all layers. The problem of selective recording and readout can be solved using reference and readout beams propagating in planar wave-guides placed between adjacent BR layers (see Fig. 2, 3a). A common write beam would be introduced into the wave-guides by
means of edge coupling for the input, and coupled via a surface grating for the output. A combination of spatial and phase multiplexing can also be employed to enable significant multiplexing within a given layer. The beams in the output of the grating G locally illuminate the particular spot of each BR layer where the holograms can be multiplexed using phase encoding methods. By rotating the multilayer medium relative to the stationary optical components (including the waveguide), we can spatially multiplex the set of phase-modulated holograms over the entire area of the recording layer.

Access to an individual layer (see Fig. 3b) is provided as follows: Each read/write beam is formed by one of the phase code holograms recorded on the rotatable disk D1, and coupled into the waveguide layer through its edge (see Fig. 3a). Figure 3b shows the recording geometry used to form a set of orthogonal phase code beams at the output of the grating (G). The interferometric mirrors, placed above each BR layer, have band-pass characteristics tailored to pass the reconstruction beam, while rejecting the readout beam.

This method, which incorporates phase encoded reference beams propagating in planar geometry, can potentially provide a significant boost in storage capacity. It would also be of interest to investigate alternative geometries for phase multiplexing. As a next step, we would investigate use of angular multiplexing, which can potentially provide even higher storage density.
OTHER IDEAS

1.) Optical networks: We have shown experimentally that the incremental recording of several point source beams at one wavelength forms, in real time, holograms which can effectively link, using a different wavelength, a particular laser source element (one of many in an array of point source elements) to a particular detector element (again, one of many detectors). The holograms are recorded on BR film using the M regime, in a way that the resulting optical interconnections are dynamically reconfigurable. Figure 4 illustrates, conceptually, the proposed interconnection geometry.

Each laser and detector corresponds to a point on SLM1 and SLM2 respectively. Thus to establish, e.g., a one-to-one connection between N lasers and N detectors we need to find the corresponding pair of coordinates on SLM1 and SLM2, and expose the BR switching between these pairs in accordance with the incremental recording technique[1]. The address of the individual connection can be changed in real time (by changing the coordinates of the corresponding points displayed on the SLMs) during a time interval on the order of 50 microseconds (the time required for the BR \( \rightarrow \) M state transition). In the same manner, one-to-many (broadcast) connections as well as many-to-one connections can be realized.

2.) We are planning to investigate the following features of BR films which potentially could provide hologram reconstruction without erasure.

- It is known that the change in refractive index due to the photo-stimulated transitions of BR states can occupy a BR volume several times larger than that of the BR molecule itself. Using this property, the following readout technique is proposed:

  A BR film is illuminated by an interferometric pattern form by two (blue) plane waves. Let us assume that we choose the period between the fringes to be less than the spatial resolution limit of the BR. A hologram is successively recorded using red light. Recording takes place only in the part of the BR film where the intensity of the interferometric pattern (formed by the blue light) is minimal. Thus the other areas (where blue light induced fringes are at non-minimal intensity) are excluded from recording with red light, as the blue light in those areas drives the BR back to the base (BR\(_0\)) state. Illumination of the BR molecules located in the areas of minimal (blue) intensity leads to a change of refractive index of the BR in an area that actually extends well out from the areas of minimal intensity due to the blue light interference. Hence, if one of the blue beams is Bragg-matched with the hologram being recorded by red light, in this case the beam will effectively diffract the hologram without its erasure.

Finally, another promising idea might allow nondestructive readout using BR films with oriented membranes. All current investigations are concentrated on fixing the data recorded in the excited M-state by applying an external electric field to the oriented BR molecules. It would be interesting to consider the opposite problem: investigate the decay of the sensitivity of the BR\(_0\) (ground state) vs. applied electrical bias. If this effect is significant and we can "lock" the sensitivity of the BR, the following process of hologram recording/readout could be employed.

A hologram is recorded using red (or yellow) light. Then, at the readout stage, and electrical bias is applied, which renders those areas of the BR that are in the BR\(_0\) state relatively insensitive. Thus subsequent red light does not affect the initial state of the BR. At the same time the red light does not change the excited M-states (which are sensitive mainly to blue light wavelengths). Thus, upon reconstruction using red light, the red light will not erase the hologram. Of course, this approach would be practical only if the applied electric field does not dramatically alter the life-time of the BR (i.e. the thermal M \( \rightarrow \) BR\(_0\) transition).
Preliminary Budget Discussions:

Realizing the uncertainties in NASA funding, we anticipate that we would request a smaller budget. Because we have already acquired the necessary strategic capital equipment items necessary to conduct the proposed research (e.g., a precision motorized translation/rotation stages and a CCD equipped with an image intensifier), we would likely not need to request capital equipment in the upcoming proposal. In addition, we will not request secretarial support, would request a significantly reduced amount for office supplies, and would request reduced summer salary for the faculty involved (Drs. D.J. Mehrl and T.F. Krile). A significant portion of the budget would be dedicated towards providing salary for Research Associate A.S. Bablumian. It is anticipated that the budget request would be in the range of $80k to $85k.

Fig. 1: Noise rejection during hologram reconstruction.
BR, recording media; FH, holographic filter; Im, output image.
Fig. 2: Holographic memory a) standard current setup; b) the setup with waveguide access scheme.
G, planar waveguide coupling reference beams with individual layer; D₁, rotatable disk with various phase code holograms; rotatable disk for selecting layers; L, focusing lens.
Fig. 3(a). Readout geometry with phase-coded reference beams. IM, interferometric mirror; BR, recording layer; WG, planar waveguide with input-output grating.

Fig. 3(b): Recording geometry of holographic disk with phase codes (for one layer only).
Fig. 4: Optical network.
LA, lasers array; DA, detectors array; SLM1 and SLM2, spatial light modulators; L, projecting lens; P, image plane of the lens L.
Fig. 5: The geometry of non-volatile reconstruction of hologram recorded in thick BR-film.
Power Point Presentation for Invited Paper at LEOS, '97

Presenter: David J. Mehrl

Programmable spatial filtering with bacteriorhodopsin

M. Storrs, D. J. Mehrl, and J. F. Walkup

We describe a programmable spatial-filtering system using bacteriorhodopsin (BR) film as a program-
mable, optically addressed spatial light modulator illuminated by a single wavelength of light. We use
a computer-controlled mirror scanning system to write time-varying filter functions to the BR film and
present proof-of-principle experimental results that demonstrate several elementary filtering operations.
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Key words: Bacteriorhodopsin, spatial filtering, scanning systems, spatial light modulators.

1. Introduction

Fourier-plane spatial-filtering systems frequently
suffer from a lack of flexibility, especially when stan-
dard photographic film is used as the spatial light
modulator (SLM) bearing the filter function. Bacte-
riorhodopsin (BR) offers a flexibility not present with
photographic film by serving as a reprogrammable,
optically addressed SLM. A previous spatial-filter-
ing system employing BR film and two wavelengths
of light1 exhibited a lack of flexibility in that the filter
function was static. Our approach differs from pre-
vious systems by using a single wavelength of light
and a computer-controlled, mirror-based flying-spot
scanner to write the filter function to the BR film.
We exploit the retention properties of the BR film to
make scanning a feasible technique. Taking advan-
tage of the photocycle of BR film allows us to update
the filter function. This arrangement combines the
optical advantages of BR films with the simplicity of
scanning systems to achieve a flexible spatial-filter-
ing system.

BR film contains the photochromic protein bacte-
riorhodopsin found in the purple membrane cell wall
of the salt-marsh bacterium, Halobacterium halo-
bium.2 The protein molecules are extracted from
the bacterial cell and deposited on an optically flat
substrate. The BR molecule is characterized by cy-
clical photochromic changes. The BR molecule has
a characteristic wavelength-dependent photoabsorp-
tion profile for each of the molecular states in its
photocycle. A simplified depiction of the BR photo-
cycle2 is shown in Fig. 1. The BR molecule is ini-
tially in the BR state and has an absorption
maximum at 570 nm. At illumination by light of a
wavelength near the absorption peak, the BR mole-
cule undergoes a rapid (~3-ps) photoinduced transi-
tion from the BR state to the short-lived (~1-μs)
intermediate K state. BR then undergoes a rapid
(~50-μs) thermal relaxation to the M state in which
it has an absorption maximum at 410 nm. The M
state is relatively long lived, with a lifetime depend-
ent on the relative humidity and pH of the environ-
ment in the manufacturing of the films4 and can vary
from a few milliseconds to hours. The films used in
our experiments had M-state lifetimes of approxi-
ately 10 s. The molecules in the M state transition
back to the BR state through thermal relaxation. As
an alternative, the molecules in the M (410-nm) state
can be forced back to the BR (570-nm) state by the
absorption of light near the second wavelength (410
nm). This provides an effective method to erase
the films. The absorption spectra of the various photo-
cycle states4 are shown in Fig. 2. Note that the ab-
sorption peaks for the BR and M states are shifted
with respect to each other, although there is a signif-
icant overlap.

BR holds promise as a SLM because of its high
sensitivity (typically 30–80 mJ/cm²), rewritability
(more than 1 × 10⁶ cycles without observable degra-
dation),5 fast response (typically 50 μs),6 high spatial
resolution (exceeding 5000 lines/mm)7 because of the
small molecule size, long-term physical and chemical
stability, and ease of manufacture.8

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At constant illumination with light of a single wavelength (e.g., 514 nm, one of the predominate lines of an argon-ion laser), the BR molecules undergo a photoinduced transition from the BR state to the M state, and simultaneously molecules in the M state transition to the BR state through both thermal relaxation and photoinduction. A steady-state population of molecules in the M state is quickly achieved (because of the 50-μs response time), and the absorption (and consequently the intensity transmittance) of the BR film takes on a value dependent on the intensity of the incident illumination. The intensity-dependent transmittance of a thin BR film can be described by $\tau(I) = \exp(-\alpha(I)d)$, where $\tau$ is the local intensity transmittance of the BR film, $\alpha(I)$ is the intensity-dependent local absorption coefficient, and $d$ is the thickness of the film. Illuminating the BR film with a relatively intense write beam allows the resulting intensity-transmittance pattern to be used as a SLM for a less intense object beam.

Scanning systems offer high spatial resolution, economy, and convenience when compared with costly SLM's. The relatively long retention time of our BR films (~10 s) provides ample time for our mirror-based scanning system to write a complete filter pattern to the BR film. Time concerns can be further alleviated by the use of a high-speed scanning system, such as an acousto-optic (AO) scanning system.

The BR film also undergoes local changes in the refractive index on illumination.9 This spatial refractive-index distribution will, in general, modify the system output; however the filter functions we wrote to the film were binary in nature, so the trans-

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Fig. 1. Simplified depiction of the photocycle for bacteriorhodopsin.

Fig. 2. Absorption spectra of the intermediate states in the photocycle of bacteriorhodopsin: BR 570, BR state at 570 nm; K 610, K state at 610 nm; M 410, M state at 410 nm.

Fig. 3. Schematic diagram of the dynamic spatial-filtering system.

Fig. 4. Images of (a) the test object and (b) its Fourier transform.
mitted object beam experienced a constant phase shift. Consequently the effects of refractive-index variations could be neglected in our experiments. In a system in which continuous filter functions are written to the BR film, additional analysis may be required to assess the effects of the resultant phase modulations.

2. Experimental Setup

The proof-of-principle dynamic spatial-filtering system we investigated is shown in Fig. 3. An argon-ion laser beam, operating at the 514-nm line and at approximately 50 mW, with a beam diameter of approximately 1.3 mm, was split into an object beam and a filter write beam. A pair of shutters are included to block the filter write beam and the object beam between experimental runs. The expanded beam illuminating the input object was passed through a neutral-density (N-D) filter with an optical density of 2 to produce a low-intensity object beam, so as to minimize the relative transmittance changes it produces in the BR film. The object beam was applied continuously throughout the run of the experiment. Lens L1 \( (f = 910 \text{ mm}) \) forms the Fourier transform of the object at the plane marked FP. For convenience we positioned lens L2 \( (f = 150 \text{ mm}) \) to magnify the Fourier distribution of the object at the plane marked FP' by approximately a factor of 4. We placed the SLM bearing the filter function at this plane to pass the desired frequency components of the input object selectively. Lens L3 \( (f = 910 \text{ mm}) \) images the filtered object beam onto a CCD camera that serves to record the resulting filtered and demagnified (by approximately a factor of 0.25) image. A frame grabber was used to record a single frame of the CCD camera image.

The filter function was written to the BR film by a computer-controlled scanning system. An AO cell was positioned in the filter beam to serve as a high-speed shutter by deflecting the filter beam into the two-dimensional (2D) mirror-based scanning system. In a more sophisticated system the AO cell could also serve to amplitude-modulate the intensity of the filter write beam. Filter functions were written dynamically to the BR film, and we relied on the film's thermal relaxation to erase the filter. In our experiments the filter write beam was positioned at an angle with respect to the object beam. This provided the advantage of simultaneous exposure of the BR film to the object beam and to the filter write beam without exposure of the CCD camera to the intense filter write beam. Lens L4 \( (f = 500 \text{ mm}) \) is
size either the horizontal or vertical elements, respectively, of the object and to low-pass-filter the remaining elements. We obtained the directional bandpass filter by writing a pair of spots to the BR film on the vertical or horizontal axis in the Fourier plane and locating them symmetrically with respect to the center of the Fourier plane. This filter serves to emphasize either the horizontal or vertical elements of the object at the spatial frequencies specified by the distances of the spots from the center of the Fourier distribution. These filter functions were selected for their ease of implementation and are shown in Figs. 5 superimposed on the Fourier spectrum of the object. Because of the relative intensities of the object and the filter write beams, only the central portion of the Fourier spectrum is visible in these figures. Striations in the images are largely video artifacts from the frame grabber.

An arbitrary filter function may be written to the BR film if the filter beam is scanned across the BR film and the intensity of the filter beam is modulated. This written function may be achieved if the mirror system is moved so as to scan the write beam in a tight spiral, thus minimizing abrupt mirror translations and continuously modulating the intensity of the beam with an AO cell.

3. Experimental Results

Experiments were conducted with a time-varying directional filter that alternately emphasized the vertical and horizontal elements of the object. Single frames of the results obtained with both filters are shown in Figs. 6. For presentation purposes the contrast of the images has been maximized. We observe from Fig. 6(a) the enhanced vertical stripes and the blurred horizontal stripes of the test object that result from low-pass filtering. From Fig. 6(b) we observe the enhancement of the horizontal elements of the object and blurring of the vertical elements, again resulting from low-pass filtering. Dynamic filtering was demonstrated by the alternate application of the vertical-element filter for approximately 1 s; this was immediately followed by the application of the horizontal-element filter function for approximately 1 s.

Additional experiments were conducted by use of an alternating bandpass filter that was also dynamically altered to pass decreasing spatial frequencies. This dynamic alteration serves to emphasize the object's vertical and horizontal elements of decreasing spatial frequencies alternately. A time sequence of these results is shown in Figs. 7. The images in Figs. 7 were captured under the same conditions, and the relative increase in brightness for different spatial frequencies is due to spatial filtering. For presentation purposes the contrast of the images has been maximized. In Figs. 7(a) and 7(c) the effects of a vertical-element bandpass filter of varying spatial frequencies is demonstrated. In each of these figures the horizontal elements of the test object are blurred and the vertical elements of the spatial frequency that was specified by the filter function are

positioned to demagnify the spot diameter in the FP' plane by a factor of approximately 0.25. The writebeam spot diameter was approximately 0.3 mm. The energy density used in the filter write beam was approximately 10 mJ/cm².

The test object chosen for our proof-of-principle experiments was a U.S. Air Force resolution-test-chart pattern consisting of vertical and horizontal stripes at varying spatial frequencies. The test mask has an overall aperture of approximately 12 mm and spatial frequency components ranging from 1 line pair/mm to 228 line pairs/mm. The Fourier transform of this object lies primarily along the vertical and horizontal axes in the Fourier plane. We took advantage of this fact in choosing the filter functions to be written to the BR film. The object and its Fourier spectrum are shown in Figs. 4(a) and 4(b), respectively. The blurring seen in Figs. 4 is largely an artifact of the frame grabber. The enlarged central portion of the Fourier spectrum in Fig. 4(b) is a result of blooming in the CCD camera.

The filter functions chosen to demonstrate dynamic spatial filtering were directional low-pass and bandpass filters. We implemented the directional low-pass filters by writing a transmissive stripe to the BR film along either the vertical or horizontal axis in the Fourier plane. This filter function serves to empha-
enhanced. Figures 7(b) and 7(d) illustrate the effects of horizontal-element bandpass filters of varying spatial frequencies. Figure 7(d) shows horizontal elements of a higher spatial frequency emphasized in the upper right-hand corner of the image; Fig. 7(c) shows vertical elements of a higher spatial frequency emphasized in the middle left-hand portion of the image. Figure 7(b) shows horizontal elements of a lower spatial frequency in the upper left-hand corner of the image; Fig. 7(a) shows vertical elements of a lower spatial frequency emphasized in the upper center portion of the image. Dynamic filtering was demonstrated by the alternating application of vertical and horizontal bandpass filters (again, each filter was applied for approximately 1 s) and the selection of progressively lower spatial frequencies by means of decreases in the distance between the spot pairs.

4. Conclusion
In summary, the use of BR films in conjunction with a scanning system has been demonstrated as an optically addressed spatial light modulator in a programmable Fourier-plane spatial-filtering system. Experiments have demonstrated several elementary filtering operations.

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References
M-type thick holograms in bacteriorhodopsin films with a high-divergence reference beam

Arkady S. Bablumian, Thomas F. Krile, David J. Mehrl, and John F. Walkup

The capacity to use differing read and write wavelengths for reconstructing volume holograms recorded in a shift-multiplexing geometry is analyzed and realized for M-type volume holograms recorded on bacteriorhodopsin films. The intensity distribution in the reconstructed wave is calculated as a function of the parameters of the recording and readout beams. Optimal recording and retrieving geometries, as well as a precise method for tuning the readout setup, are suggested. © 1998 Optical Society of America

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1. Introduction

High-capacity storage of optical information can be achieved by holographic recording throughout the volume of a thick medium. The strong sensitivity of thick holograms to the parameters of the reconstruction beam allows one to multiplex many holograms in the same volume and then read them out selectively. The simplest way to retrieve any desired hologram is to use a readout beam identical in all respects to the reference beam used for recording. At the same time, for nondestructive retrieval of stored holograms it is necessary either to fix them or to reconstruct them at wavelengths to which the material is insensitive. (The latter is of particular interest in the general area of real-time optical data processing.) In general, changing the readout wavelength will change not only the output's orientation (in accordance with the Bragg condition) but also the shape of the wave front. This leads to both a loss of information in the object beam and difficulties associated with the synthesis of a readout beam with a complicated wave-front shape.

Hologram reconstruction with different wavelengths that employs distortion compensation during reconstruction by means of changing the curvature of the readout wave front was described in Ref. 2. In the paraxial approximation using the coupled-wave theory, the authors calculated the optimal parameters for the readout beam (focal length) and assessed the width of the reconstructed spherical beam. Unfortunately, under the approximations used in Ref. 2 this approach cannot be applied for analyzing several interesting hologram-multiplexing geometries for situations in which recording beams are highly divergent spherical waves. Such a geometry was investigated in Ref. 3, which described a hologram of an information-bearing signal considered to be a superposition of plane-wave elemental holograms with the same spherical reference beam. The plane-wave object beam of each elemental hologram represented a single component of the signal. This approach allowed the authors to calculate the optimal parameters of the reconstructing beam—a shift parameter characterizing hologram selectivity—and an assessment of maximal resolution in the reconstructed image.

In this paper we apply another approach in which we consider the relative change of the intensity distribution in the frequency plane of the signal. For an arbitrary wavelength we calculate the reconstruction of the points of the Fourier transform of a signal by considering the hologram as a superposition of elemental holograms, each being formed by two point sources. We show that, besides the parameters mentioned above, such an approach allows one to assess distributions of both relative intensity and resolution along the reconstructed image. These parameters are then compared with values derived experimentally.

It is necessary to note that the readout beam has to be calculated and oriented with respect to the hologram with high accuracy, according to the shift se-
The next step was to develop a method for tuning the optimal location of the readout beam. So our applied easily without some practical method of finding accuracy, it becomes clear that the results cannot be applied easily without some practical method of finding the optimal location of the readout beam. So our next step was to develop a method for tuning the readout setup. Finally, experimental verification of the theory is demonstrated by use of M-type holograms in bacteriorhodopsin (BR) films.

2. Theory

Let the hologram be recorded by the reference $u_1$ and object $u_2$ waves, as shown in Fig. 1. In both recording arms the laser beams are expanded and then point focused. This allows both the formation of a spherical reference beam and the insertion of the information into the object arm by use of a transparency. It is evident that each elemental hologram can be reconstructed by the beam whose parameters coincide with those of one of the recording beams. The existence of reconstructed beams whose wavelengths differ from the recording wavelength becomes clear from the following: Each elemental hologram is recorded by point-source beams; therefore any of its small parts is described by the constant grating vector $K$. This means that, for an arbitrary wavelength $\lambda$ in every point $(x, y)$ of the elemental hologram, two rays (incident and diffracted) oriented at the Bragg angle to the grating vector $K$ are determined unambiguously. The lattice of rays combines to form only two beams that can be diffracted by this hologram and that, generally speaking, for an arbitrary wavelength $\lambda$ are not spherical.

Let us consider hologram reconstruction by a spherical wave $u_3$ with coordinates $(x_3, y_3)$ and determine the Bragg mismatch angle $\delta$ for its rays at every point of their crossing within the hologram. Let us also consider the cone of rays emanating from $(x_3, y_3)$ with an average spatial frequency $\beta_2$. The angular aperture of this cone of rays we choose is small enough to consider it to be a plane wave. Our purpose is to define the conditions under which (1) the intensity change along the cone in hologram $H$ is equivalent to (2) the intensity change of a plane wave incident on a plane diffraction grating. Such an analogy will allow us to assess the diffraction in the case 1 by calculation of the diffraction in case 2 in accordance with the coupled-wave theory. Under suitable approximations, described below, the intensity of the plane wave in the output plane of the equivalent diffraction grating will be equal to the output intensity of the cone of rays. Continuing this procedure for all $\beta_2$, we can calculate the output intensity arising from the source $u_3$. Then one can calculate the intensity distribution of the diffracted beam for each elemental hologram $H$, considering the sum of the incident and diffracted beams to be constant. The sum of the elemental holograms corresponds to the Fourier spectrum of the transparency $T$, by which we can estimate the resolution in the reconstructed beam.

First, let us consider the main arguments supporting the proposed approximation, as well as the limits of its applicability. The diffraction process is determined mostly by the direct energy diverted from the incident into the diffracted beam when the values of the diffraction efficiency (DE) are low (typically the case for BR). It follows from the fact that the amplitude change of the incident wave is proportional to the amplitude of the diffracted wave, and vice versa, that the amplitude change of the diffracted wave is proportional to the amplitude of the incident wave. Therefore the diverted energy proceeds mainly in one direction when the difference between the amplitudes of the interacting waves is large. Let us neglect the influence of the parameters of the diffracted beam on the intensity change of the incident beam. This assumption and the fact that the incident rays
molecules, transforming them into the M-state ready for recording with blue light. Using M-type holograms allowed us to investigate the two-lambda method of constructing the holographic memory and, simultaneously, to change and compare in real-time the recording and readout parameters.

Mutant variant BR$_{D96N}$ films with a thickness of 100 $\mu$m were used. A hologram of a standard U.S. Air Force test pattern was recorded at $\lambda = 458$ nm and reconstructed at $\lambda = 633$ nm. The setup geometry for recording and reconstruction was chosen according to the theory described in Section 2, enabling us to compare the experimental results with the results derived theoretically (see Figs. 2–4).

As was pointed out above, in a recording regime with a high sensitivity to shift the process of finding the location of the readout beam with the given parameters becomes a difficult problem practically. This is particularly true for high values of the Klein parameter $Q$. For optimally tuning the readout setup the following method was suggested and utilized: The thick recording medium was first replaced by a structure consisting of two separated thin films. A hologram recorded in such a structure, in contrast to a common thick hologram, can be reconstructed by readout beams of any orientation. This forms two images that are propagated, in general, in different directions. On optimal orientation of the readout beam these directions coincide, and interferometric fringes of overlapped images coalesce into one fringe. From the maximal size of this fringe one can judge the accuracy of the reconstruction source location.

For modeling the volume medium a 1-mm glass plate with photoresist layers on both surfaces was used. The readout beam was formed by use of a piece of optical fiber to facilitate precise positioning of the point source. After finding the optimal position for the reconstruction source, we then replace the model medium with the BR film. We also devised a technique (not discussed here for the sake of brevity) to compensate for the fact that the overall thickness of the model medium and the BR film are not the same.

Fig. 5. Photographs of transparency $t$ from hologram $H$ and the corresponding plots of reconstructed beams from two elemental holograms, $H(r = 0)$ (upper traces) and $H(r = 1 \text{ mm})$ (lower traces), in the exit plane of hologram $H$ for (a) $Q = 100$, (b) $Q = 300$, and (c) $Q = 750$. 
Figure 5 presents photographs of the U.S. Air Force test-pattern image reconstructed from the BR film with different values of the $Q$ factor. For comparison, next to each photograph we show plots of the intensity profiles of beams diffracted from two elemental holograms, $H(0, 0)$ and $H(r = 1 \text{ mm})$, recorded in the corresponding geometry. As was pointed out above, a sufficient DE for these two elemental holograms automatically ensures a sufficient DE for all elemental holograms $H(|r| \leq 1 \text{ mm})$ (remember that $r$ is the coordinate in the frequency domain). With the parameters of the beam $u_2$ taken into account, it is easy to calculate that the reconstruction of a 1-mm-extent $u_2$ in the frequency plane provides a 30-μm resolution in the reconstructed image [Eq. (2.7)]. As one can see, this resolution (the width of the first element in the fourth group of the test pattern), which conforms to the lower traces in Figs. 5(a)–5(c), is provided over all the field of the reconstructed image for $Q = 100, 300$ but is reduced for $Q = 750$. These results are supported by analysis of the corresponding photos. The experimental sensitivity of the setup with $Q = 750$ to the shift of the readout beam was approximately 20 μm, deviating by 5%–6% from the theoretical prediction. The measured DE of the reconstructed images was approximately 4%–5%.

4. Conclusions

We have demonstrated a relatively simple method of calculating critical parameters for the processes of reading and writing volume holograms using highly divergent beams of differing wavelengths. The experimental results were shown to agree with the theoretical results. We have considered the resolution and relative-intensity distribution of the reconstructed image stored in a thick hologram by a high-divergence reference beam that is arbitrarily oriented relative to the object beam. These parameters, as well as the optimal parameters of the read-out beam, can be estimated from the intensity profiles of beams diffracted by two elemental holograms (recorded by a pair of spherical beams), whose simple calculation method has been presented above.

A method for modeling a volume hologram by use of a medium consisting of two separated thin layers has also been suggested. This approach allows one to find experimentally the precise optimal position of the readout beam. Also, the method makes accessible the modeling and direct visualization of the process of diffraction by thick holograms with arbitrary recording parameters. These procedures could be difficult or impossible as a result of the characteristics of commonly used volume recording media (e.g., short lifetimes, low DE, destructive readout, etc.).

We thank Bend Research, Inc., for BR-film preparation. This study was supported by the NASA Ames Research Center, whose support is sincerely appreciated.

References

from \( u_3 \) intersect one and only one conical region of the hologram allow one to consider the diffraction in such conical regions independently of each other. It means that the diffraction of the beam \( u_3 \) within a region determined by \( \beta_3 \) will not be changed after the arbitrary changing of the hologram's structure, as well as the shape of the beam \( u_3 \) outside the region. In particular, diffraction by hologram \( H \) within a region will be equivalent to the diffraction of the plane wave with spatial frequency \( \beta_3 \) on a hologram whose grating vector \( K \) varies as a function of \( y \) in the same manner as that in the given region of hologram \( H \) and is independent of \( x \).

Let us now break this new holographic structure into parallel layers \( Y_{k-1} < y < Y_k \). We choose the thickness of each layer to be thin enough to consider \( K(y) \) to be constant within the layer. In this case the intensity change of the incident plane wave within each layer can be calculated in accordance with the coupled-wave theory. We can see from Eq. (2.5) below that the equation describing the diffraction depends on only the Bragg mismatch angle \( \delta \) if we use a first-order Taylor approximation for \( \delta \) and \( K \). It means that changing the value of \( K \) in any layer without changing \( \delta \) does not change the intensity of the incident beam in the output plane of the hologram. This, in turns, means that the grating vector \( K \) can be chosen to have the same value for all layers with the condition that \( \delta \) is constant. Thus, assuming \( \delta \) is not changed along the propagation path of the cone of rays constituting \( u_3 \), we can calculate the output intensity by calculating the diffraction of the plane wave on the equivalent diffraction grating. The spatial frequency of the plane wave and the absolute value of the grating vector \( K \) have to be chosen to be equal to \( \beta_3 \) and \( K(x, 0) \), respectively.

As indicated in Fig. 1, rays from the recording \((x_1, y_1), (x_2, y_2)\) and reconstructing \((x_3, y_3)\) sources traveling to an arbitrary point \((x, 0)\) on the recording medium make an angle \( \theta_i \), where

\[
\theta_i(x, y) = \arctan \left( \frac{x_i - x}{y_i - y} \right), \quad i = 1, 2, 3. \tag{2.1}
\]

The Bragg angle at the same point is

\[
\theta_{\text{Bragg}}(x, y) = \arcsin \left[ \frac{\lambda_2}{\lambda_1} \sin \left( \frac{\theta_1(x, y) - \theta_2(x, y)}{2} \right) \right] + \theta_1(x, y) + \theta_2(x, y), \tag{2.2}
\]

which follows directly from the Bragg law written in common form\(^2\) for readout \( \lambda_2 \) and recording \( \lambda_1 \) wavelengths. Consequently, the Bragg mismatch angle \( \delta_{\text{Bragg}} \) is

\[
\delta_{\text{Bragg}}(x, y) = \theta_{\text{Bragg}}(x, y) - \theta_1(x, y). \tag{2.3}
\]

We choose the coordinates of the point-source reconstruction beam \((x_3, y_3)\) in such a way that two of its rays crossing the hologram at points \((0, 0)\) and \((c, 0)\) make Bragg angles with the input plane [Eq. (2.2)]. Using geometric construction we can show that

\[
y_3 = c \cos[\theta_{\text{Bragg}}(0, 0)] \cos[\theta_{\text{Bragg}}(c, 0)] - \sin[\theta_{\text{Bragg}}(0, 0)] - \theta_{\text{Bragg}}(c, 0), \tag{2.4}\]

where \( \theta_{\text{Bragg}} \) for the rest of the rays of the reconstructed beam and insert it into the relation that expresses the angular sensitivity of a thick hologram:

\[
\eta = \left| \exp \left[ -\frac{i\delta}{c_s} \right] \times \exp \left[ -i\xi \frac{\exp(i\xi^2 + \nu^2) - \exp(-i(\xi^2 + \nu^2)^{0.5})}{2(1 + \xi^2)^{0.5}} \right] \right|, \tag{2.5}
\]

where \( \xi = (2\pi n/\lambda_2)\delta_{\text{Bragg}} d \sin[(\theta_1 - \theta_2)/2] \), with \( \nu = \chi d/c_s \), \( c_s = \cos[(\theta_1 - \theta_2)/2] \), \( d \) is the thickness of the hologram, and \( \chi \) is the coupling constant.\(^4\) Expression (2.5) describes, in the exit plane of the hologram, the profile of the intensity of the diffracted wave that attains its maximum at points \( x = 0 \) and \( x = c \). Note that we are interested in the relative DE of diffracted rays versus only \( \delta_{\text{Bragg}} \) for each of them, so we can simplify Eq. (2.5) to obtain

\[
\frac{\eta}{\eta_0} = \nu^2 \sin^2[\pi (\nu^2 + k\delta_{\text{Bragg}}^2(x, y))^{0.5}]. \tag{2.6}
\]

Here we took into account the fact that the presence of loss has very little influence on the angular sensitivity\(^4\) and used Eq. (2.5) as written for lossless gratings with real \( \chi \). The constant \( \nu \) was measured experimentally.

Figure 2 represents the relative-intensity distribution profile (equivalent to the normalized DE) of diffracted beams in the exit plane of the hologram calculated for the elemental hologram \( H(0, 0) \) (corresponding to the zeroth-order component of the Fou-
rier spectrum $T$ of transparency $t$) for reconstructed beams with different values of the parameter $c$. Values of $\lambda_1 = 458$ nm and $\lambda_2 = 633$ nm were used for this and subsequent plots. The $X$ axis is in the hologram recording plane, and the different values of $c$ are obtained by the changing of the location of the reconstruction point source $(x_3, y_3)$. Optimized readout parameters correspond to the portion of the hologram where the curves of Fig. 2 have sufficient DE, saynot less than $1/e$ (as for the definition of the width of a Gaussian-shaped signal), and are as flat as possible. In our experiments (Section 3) the hologram was approximately $3$ mm in extent, so $c = 2$ mm would be optimal from Fig. 2.

Profiles of diffracted beams with the optimized parameter $c$, calculated for several recording setups of $H(0, 0)$ holograms (with different orientations and average spatial frequencies of their recording beams), are shown in Fig. 3. The diffraction of the beam optimized for the reconstruction of hologram $H(0, 0)$ from holograms $H(\Delta x, \Delta y)$, which correspond to the higher-order components of the Fourier spectrum $T$, is shown in Fig. 4. These plots represent the sum intensity distribution of beams diffracted by elemental holograms $H(\Delta x, \Delta y)$ and $H(-\Delta x, -\Delta y)$, where we use the fact that symmetric components of the Fourier spectrum contain the same information. From Fig. 4 we can see that the relative DE decreases with increasing values of $r$, corresponding to holograms of higher components of the Fourier spectrum $T$. Thus the reconstruction system acts like a low-pass filter, and one can use this curve to define an effective spatial cutoff frequency at some particular value of the relative DE ($1/e$ in this paper).

Let us now consider in more detail how the intensity profiles of beams diffracted by elemental holograms (Figs. 2–4) can be utilized to determine the resolution and intensity distribution in the reconstructed image $I$. Each point $P$ of the recording transparency $t$ is formed by a cone of rays connecting it with points of the Fourier spectrum (Fig. 1), each of which we took as an elementary point-source object beam of the elemental hologram. The part of the transparency $t$ in the vicinity of the point $P$ will be reconstructed with a resolution $h$ if all rays of a cone with a base radius of $r$ have enough DE ($\eta > \eta_0/e$), where $r = (\Delta x^2 + \Delta y^2)^{0.5}$ is one of the coordinates of the Fourier plane of the transparency $t$ and $D$ is the distance between the plane of transparency $t$ and its Fourier transform plane $T$. If the behavior of the plots in Fig. 4 is taken into account, the proper DE of only edge cone rays corresponding to the maximum-order components of the Fourier spectrum will provide the required resolution. Then it is easy to see that the intensity distribution of the reconstructed beam at the image plane corresponds to a profile of the beam diffracted by the $H(0, 0)$ hologram at its exit plane, reduced in size by $D_2 \cos \theta_{ave}/D_1$, where $D_1$ and $D_2$ are the distances between the Fourier plane of image $i$ and, accordingly, the hologram and the plane of the image, respectively, and $\theta_{ave}$ is the average incident angle of the reconstructing beam. Thus the intensity and resolution in an arbitrary part of the reconstructed image $T$ can be estimated by the profiles of two beams diffracted by elemental holograms $H(0, 0)$ and $H(\Delta x, \Delta y)$, where $\Delta x$ and $\Delta y$ obey the condition of Eq. (2.7).

Let us also consider the limits that the assumptions defined above place on the thickness of the hologram (more exactly, on the Klein parameter $Q$, which characterizes thick gratings$^3$ for which the theory is valid). Calculations [Eqs. (2.1)–(2.6)] showed that, for a thickness of approximately $0.5$ mm and values of the $Q$ factor of the order of $10^4$, the values of $\delta$ variations along the propagation path of the reconstructing beam do not exceed $10^{-4}$ rad, which corresponds to a percent error in the intensity calculation of not more than $5\%-7\%$.

### 3. Experimental Results

To investigate the different wavelength regimes of recording and reconstructing volume holograms we used a thick BR film. This material exhibits excellent properties for real-time optical processing applications, as well as for permanent high-density data storage.$^6$ Hologram recording in BR films was carried out in the M-type regime, in which red readout light provided at the same time excitation for the BR
1/17/97

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Optical Data Storage and Processing
Applications of Bacteriorhodopsin for
deplete the water of oxygen.
energy from the sun, when e.g. competing algae
mechanism to survive by photo-synthesizing
used to allow the bacterias as a "backup"
Halobacterium Halobium (purple membrane).
naturally occurring salt marsh bacterium

• A polyCytochrome protein extracted form a

What is BacterioRhodopsin(BR)?
*Whereas native BR are grown in salt water, mutant forms are grown in Lubbock City tap water.*

- 
  - "membrane" and more recently "blue membrane" forms.
  - Comes in native and mutant forms (D96N). Also "purple"
  - "Bistable" phototrophic response.
  - Bistable response (70% typical, fast response (>50 µs), excellent stability.
  - High sensitivity (1-80 mW/cm²), relatively high diffraction efficiency.
  - Diffusion problems are currently being addressed.
  - Spatial resolution limited by molecular size (~5 nm) and diffusion.
  - Even convex surfaces.

- Even high quality optical films that can be deposited on planar or 
  - Very robust to extreme environments (e.g., temperature extremes).

**Features of BR**
High, similar to more expensive LCDs

can be used, e.g., to convert from incoherent to coherent

the read beam now carries the (negative) image.

BR film, selectively "eroding" parts of the grating. Thus
white light source is then used to project an image onto the
BR material. This grating diffracts the read beam (red). A
part of strong white beams (blue) write a grating into the

(5%) now.

By performing simultaneous readout (with red light) and
writing (with blue-green light), BR can act as a real-time

BR as a Spatial Light Modulator
Bend Research, Inc.

- Techniques, which are currently being investigated,

- Could be remedied by development of electrical fixtures

- Volume

- Reading out a page partially erases all pages within the

refresh scheme is employed.

- but read only occasionally, access, unless a judicious

destructive readout problem reduces BR to "write often /

days.

- BR memory retention times are limited (typically hours to

BB as a memory - problems
Researchers promise to largely remedy this problem.

By Bend Holovisic applications. A recent development severely degrades memory retention times in practice often reduced greatly due to diffusion. Diffusion is in

The tower spatial resolution or < 1000 lines/mm is in

BR as a memory problems
Techniques may be partially addressed by "expose scheduling". This problem cannot be remedied by "fixing" techniques.

Previously written pages.

Writing a page to memory partially erases all same volume.

With the number of pages simultaneously stored in the achievable differentiation efficiency to decrease geometrically. The "destructive write" problem indirectly causes the

BR as a memory - problems
Pages of Data
Motivation for Multiplexing

- Holographic multiplexing allows use of "thick" optical films, other than "thin" films. Multiple data objects cannot be stored on top of each other. Holographic multiplexing employs simple spatial multiplexing and multiple pages of data can be stored, and later retrieved from within the same volume. The additional storage volume afforded by increasing the film thickness allows the information per unit surface area (bits/mm²) to be increased dramatically. Current research with holographic technologies such as Lithium Niobate -- > 100's of pages.

- High density optical disks employ simple spatial multiplexing & use access normally used in conventional memories. "Serial" access to the objects data, instead of the usual serial bitstream. E.g. images, audio samples, data files etc. Page access allows natural for many "data objects" to be stored/retrieved in page format.
that is written into the BR medium. \[ \rho = \frac{\gamma}{(\pi / 2)} (\gamma / 2) \] Interference pattern frequency \( \rho \) - lines/mm of the "grating-like" intensity spatial angle \( \Delta \theta \) between interfering beams and the "spatial division multiplexing". Direct analogy between the angle multiplexing is analogous to "frequency angle with the original carrier (reference beam). Can later retrieve a particular data page by illuminating BR interference pattern in the BR medium. Spatially (spatially) heterodyned signal is then recorded as an intensity resulting is mixed with a carrier beam (the reference beam). Resulting angle multiplexing: Optical signal beam (carrying page of data) Volume Multiplexing Techniques; what’s behind them?"
\( \text{ARG}(E) \) describes the shapes of the wavefronts.

\( |E| \) describes the intensity of the light, and valued where \( |E| \)

this case the reference light beam. Generally complex-

describes the spatial distribution of the field of the light (in

Here \( E \) is a time-independent phasor representation that

\[
(\chi = 2\pi) \quad [E^{1} = E_{0} \cos(k \cdot \sin\theta + \varphi)]
\]

Plane wave: \( E_{1}^{1} \)

Simplified reference beam used in angle multiplication:

\( p \) for small \( \theta \) (lines per mm) - (lines per mm) \( \chi \)
Combinations of the above:
- Waves using "random phase encoding" of wavefronts.
- From "noncoincident point sources.
- Family of spherical waves "converging to" or "diverging"
- Family of plane waves with different wavelengths (WDM)
- Family of plane waves travelling at different angles.

Examples include:
- "Hilbert space" should approach zero. i.e. the projection of "basis vectors" onto each other in volume multiplexing - should form an orthogonal basis.

Necessary properties for a family of "carriers" used in

Orthogonal "carriers"
The third term contains the original recorded signal data:

\[ E \text{ sig} = |E|E^* \text{ sig} = |E|E^* \text{ rec} \]

The reconstructed signal is proportional to:

\[ E_{\text{rec}} = E_{\text{sig}} + E_{\text{sig}} + E + E^* + E^* \]

The intensity interference pattern stored in the (BR) medium:

Recording and Reconstruction Systems Level View of Holographic
Spherical waves.

In our technique, both reference and signal beams are

spatially variant instantaneous spatial frequency.

interference pattern takes the form of a chirp (with a
wave, but the "signal" beam is a spherical wave, and the
reference beam is a plane
communications. Usually the reference beam is a plane

techniques sometimes employed in "spread spectrum"

as wideband "chirped" FM carriers reminiscent of

In shift multiplexing, the "carriers" can be thought of

Shift Multiplexing
Setup for "Shift Multiplexing of Holographic Data Pages"

Disk read/write access mechanisms.

And compatible with current optical and magnetic

Shift multiplexing: Relatively simple to implement,
original image of the data page.

- Upon readout, a second lens can be used to reconstruct the
  the BR volume.

- With each data bit is stored in a "distributed" manner throughout
  the BR medium, the BR medium is shifted (translated) slightly
  after a page of "carrier" takes the form of a "spherical wave".

- Instead of recording a direct image of data page, a lens is used
  by mechanical actuators:

- Shift translation:
(Circular regions)

Volume. By virtue of the `overlapping` of pages

Note multiple data pages are stored within a common

Circle denotes a page of stored data.

(b) Depiction of page addressing in shift multiplexing, where each

Figure 3: (a) Depiction of three superimposed gratings in a local volume.
When employing holographic volume multiplexing, the use of different wavelengths introduces unique problems with wavelength (i.e., where \( \frac{\partial \alpha}{\partial \gamma} \) is maximal).

The index of refraction modulation tends to be greatest at wavelengths where the absorptance changes most rapidly. The index of refraction problem can be reduced considerably.

In this way the modulating, but absorptance is reduced. In this way the index at \( \lambda = 500 \text{ nm} \) where there is a large refractive index at one another (\( \lambda = 570 \text{ nm} \) absorptance peak for good write sensitivity, and read it out at another (\( \lambda = 570 \text{ nm} \)). For example, let \( \lambda \) correspond to the plane wave, and read it is desirable to write to BR at one wavelength (\( \lambda \)).
Phase-contrast reconstruction. Source 6 μm. Some (spatially variant)

Setup for 2-λ Shift Multiplexing in BR
(hence system is compact, and easier to align).

- Use of "point sources" allows use of optical fibers
  is inconsequential.

(in our case) reduced in size. This effect, however,
the reconstructed image is relocated in space, and
not too badly).

spatial resolution of the reconstructed image (but
A space-variant Bra
g mismatch effect limits the
issues associated with this approach.)
data.

the territory if we are to multiplex many pages of
WDM, spatial alignment sensitivity comes with
read/write access techniques (e.g. as opposed to
that the system is doing its job. As we use spatial
High sensitivity to alignment actually indicates

- High sensitivity to alignment.

- To facilitate alignment.

developed a clever experimental technique
3-D space. Dr. Arkady Bablumian has
tolerances of a few microns in
The tip of the "readout fiber" must be aligned to

Alignment Issues
research are portable to many other optical materials as well.
The read/write access technologies developed in our
this is not what we are being funded to research.
using BR as a holographically spatial light modulator, but
BR is in real-time signal/image processing applications
One of the most attractive applications we have found for
as photorefractive materials and photopolymers.
issues are also faced by "conventional" optical materials such
before BR memory becomes practical. Yet many of these
BR has many critical issues that need to be addressed.

Concluding Remarks