Invited Paper

Holographic Memories

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Abstract

Holographic memories can be read-out either with the reference or the signal beam. Reference beam read-out reconstructs the stored data whereas signal beam read-out performs a search of the stored data base. This dual mode of holographic memories is explored for the various methods that have been developed for multiplexing holograms.

Introduction

The recent advances in holographic memories have made it possible to routinely store thousands of holograms at a single location and retrieve the stored data with sufficient fidelity to make holography a promising candidate for high capacity, high bandwidth storage in digital computers [1]. Holographic memories also have the interesting property that they can be easily configured either as location-addressable or a content-addressable. This is a consequence of the following property of holography: Either of the two beams that are used to record a hologram approximately reconstructs the other one. When the reference beam reconstructs the hologram, the stored signal is reproduced yielding the more conventional location addressed holographic memory. When the signal beam illuminates the hologram, an approximate reconstruction of the reference results. By measuring the fidelity with which the reference is reproduced we obtain an estimate of the degree of similarity between the signal beam used during recording and the one used for read-out. For a single hologram, read-out with the signal beam reduces to the familiar correlator. For a holographic memory, in which multiple holograms are stored, reading out with the signal beam yields an array of correlators or an associative memory. Since memories with up to 10,000 holograms at a single location have been demonstrated, it is now possible to implement relatively simple systems that implement several thousands correlations in parallel. This capability can be used to solve image recognition problems that are much more complex than what we can now tackle with single a correlator.

In this paper we exlore the duality between holographic memories and correlators arrays for the various multiplexing schemes that have been used to store muliple holograms. We show that each multiplexing method performs very differently. The basic trade-off is between shift invaricance and the ability to visualize mutliple correlators in parallel. We will describe each multiplexing method separately and we will then compare their performance at the end of the paper.

Angle Multiplexing

The optical system for recording and reading angle multiplexed holograms in the 90 degree geometry is shown in Figure 1. Data is presented on the spatial light modulator (SLM) and the hologram is formed by interfering the 2-D Fourier transform of the signal and a plane wave reference beam that enters the crystal from the orthogonal facet. Multiple pages are multiplexed by altering the angle of incidence of the reference beam while updating the data recorded on the SLM. A mechanical beam deflector is typically used to control the angle of the reference beam. When the recorded holograms are illuminated with the reference beam at the proper angle, any one of the stored holograms can be reconstructed on the detector array marked DA1 in Figure 1. Alternatively, the hologram can be read-out through the signal pathway. A probe image is recorded at the SLM its Fourier transform illuminates the hologram. The light diffracted by the hologram in this case is an approximate reconstruction of all the plane reference beams used to record the holograms. More precisely, if we neglect for the moment the effect of the finite thickness of the hologram, each reconstruction is spatially modulated by the product of the Fourier transforms of the probe and stored images. The reconstruction is then Fourier transformed and the result is detected on the detector array marked as DA2 in Figure 1. Consequently the correlation between the probe and each of the stored images. The correlation patterns are spatially displaced with respect to each other in the x direction because the angular multiplexing causes the correlations to be shifted at the output plane. When the holographic medium is thin, then the correlation patterns are overlapping with one another. If the probe beams matches one of the stored holograms then a sharp autocorrelation peak forms at the output at the location where the plane wave reference beam that is used to record the hologram comes to a focus on DA2. Therefore the identity of the probe can be inferred from the position of the correlation peak. However, if the input can be a shifted version of one of the stored holograms, there is an ambiguity in interpreting the presence of a correlation peak at the observation plane. This ambiguity is resolved when the hologram is thick because only a small central slice of the correlation pattern is displayed . Multiple correlations can be unambiguously viewed in this case but the price is loss in shift invariance in the x direction. If the probe image is shifted in x the correlation peak disappears whereas if the probe is shifted in y the correlation peak also shifts.

The number of correlations that can be simultaneously viewed in this way is given by the ratio of the maximum angular deviation of the reference beam (typically 20 degrees) divided by the angular selectivity of the holographic memory which can be 1/100 of a degree. Therefore, more than one thousand correlations slices can be simultaneously viewed. In addition, the reference beam angle can be scanned in the second dimension as well during recording. This will displace the correlation patterns in the y direction. Typically, the y displacement is chosen to be large to eliminate the ambiguity in interpreting the correlation patterns at the output leading to 5 or so rows of correlation slices. Mok [2] has experimentally demonstrated the storage and correlation of 5,000 images in this way.

Wavelength Multiplexing

Holograms can also be multiplexed by changing the wavelength of the illumination instead of the angle of the reference beam [3,4]. The reflection geometry maximizes the wavelength selectivity (the minimum change in wavelength that Bragg mismatches a stored hologram) and therefore this geometry, shown in Figure 2, is commonly used for the recording of wavelength multiplexed holograms. Wavelength multiplexed holograms can also be read-out with the signal beam by recording a probe image on the SLM and illuminating it with a laser beam at one of the recording wavelengths. The Fourier transform of the probe image illuminates the hologram and the reconstruction is reflected back towards the SLM [3]. As in angle multiplexed holograms, the reconstruction a plane wave that is multiplied by the product of the Fourier transforms of the probe beam and one of the stored holograms which yields the correlation after the reconstruction is transformed onto DA2. The difference is that in this case the correlation with only one of the stored holograms (the one whose wavelength at the recording stage matches the read-out wavelength) is displayed at one time. On the other hand, the entire correlation pattern is displayed and therefore there is full 2-D shift invariance in this case. Wavelength multiplexed correlators can be useful in applications where we can use other clues to search through the database of stored holograms for a match with the input. Alternatively, if a rapidly tunable laser source becomes available then the correlations can be performed sequentially. Perhaps the highest utility of wavelength multiplexing maybe its use in conjunction with another multiplexing technique, such as angle multiplexing. In this case a parallel search can be performed for the set of angle multiplexed holograms at one wavelength and wavelength retuning can then reveal a new batch of correlations.

Shift Multiplexing

Shift multiplexing [5,6] is a method that allows us to record multiple holograms without changing any of the properties of the reference beam. Instead, the relative position between the reference and the recording medium is altered by shifting the material or the reference. This method is particularly useful in a disk configuration [7] where the rotation of the disk naturally provides the required shift. The trick that makes shift multiplexing work is the use of a reference beam that is a spherical wave. The direction of light propagation locally on the spherical wavefront varies with position. We can think of the spherical wave as being composed of many local "plane waves" that propagate at different directions at different positions on the wavefront. Therefore when a the read-out is done with a shifted spherical wave there is a local mismatch in the angle the read-out beam, similar to angle multiplexing. The shift multiplexed memory may also be configured as a correlator array by simply illuminating the recorded holograms with the signal beam in the 90 degree geometry shown in Figure 3. This results in the reconstruction of all the spherical references, shifted with respect to one another. Each of the reconstructed references is modulated by the product of the Fourier transforms of the input and the stored reference. Each reconstructed spherical reference comes to a focus resulting in a lens-less Fourier transform which yields the correlation function between the probe image on the SLM and all the stored images. Shift multiplexing, like angle multiplexing, yields only 1-D shift invariance but it allows the simultaneous display of a large number of correlations (~1,000). The nice advantage of a shift multiplexed correlator, compared to an angle multiplexed one, is that it can be implemented without lenses .

Phase Code Multiplexing

In a phase code multiplexed memory [8] the reference beam is also not a plane wave. It consists of many plane waves, with the amplitude and phase of each being modulated in order to multiplex multiple holograms. Typically a second phase SLM is used in the reference arm (Figure 4) to introduce the modulation of the various components of the reference. When used a memory, the proper code is presented on the SLM in the reference arm and the corresponding image is retrieved on the detector array that is marked DA1 in Figure 4. Notice that there is a complete symmetry between the signal and reference arms in this architecture. Therefore, we expect that if we present one of the stored images on the SLM in the signal arm, then a reconstruction of the corresponding phase code will appear on DA2. The intensity of any phase code reconstruction is uniform and therefore this would be a very uninteresting system. We can convert this system into an associative memory [9] by using amplitude (typically binary patterns) rather than phase patterns in the reference arm. Then when each stored image is presented at the probe the associated image forms at DA2. Notice, that there is a limitation on the number of pixels that can be used in the two planes. One solution that works is to use full 2-D images as probe images and 1-D associated reference patterns. This is then identical to the array of correlators that results from an angle multiplexed memory. Alternatively, we can have 1-D probes and 2-D references. We can also have anything in-between using the fractal sampling grids described in reference [9]. Such associative memories have been used in the optical implementation of multilayer neural networks.

Peristrophic Multiplexing

The architecture for recording and retrieving information in a peristrophic memory [10] is shown in Figure 5. In this case multiple holograms are superimposed by rotating the medium that is placed in the Fourier plane of a standard 4-F system. The center of rotation coincides with the intersection of the optical axis and the normal to the surface of the material. The axis of rotation is normal to the surface of the material. When used as a memory, the rotation of the material causes the reconstructions to rotate as well and move off the detector. Therefore individual peristrophically multiplexed holograms can be independently viewed either sequentially on a single detector or in parallel on an array of detectors. When the memory is probed through the signal arm, a spectrum of plane wave references is reproduced, arranged in a conical pattern. Each of the reconstructed references is modulated by the product of the transforms as previously discussed and a final Fourier transform produces the correlation between the probe and all the stored images. The correlations can be viewed sequentially (as in wavelength multiplexing) or in parallel if we are willing to use multiple detector arrays that are arranged in a large circle. Peristrophic correlators can have full 2-D shift invariance since the material can be arbitrarily thin in this case and Bragg mismatch effects do not limit the shift invariance.

Space Multiplexing

Space mutliplexing is used to increase the overall storage capacity of a memory that is multiplexed in any other way [11, 12]. Holograms are simply mutliplexed in different locations on the surface of the recording material as shown in Figure 6. A scanning mechanism must be incorporated in both the signal and reference arms to direct the two beams to a selected location. Alternatively, the medium can be mechanically translated in 2-D to position a desired location under the illuminating beams. A popular arrangement of this type is the holographic 3-D disk [7]. When a probe is placed on the SLM, its Fourier transform is directed to the desired storage location on the holographic medium using the same scanning mechanism that is used for recording the space multiplexed holographic memory. The interesting point about a space multiplexed memory is that the correlations can be all be viewed on a single detector array at the output. This is accomplished by using a large Fourier transform lens after the space multiplexed hologram that performs 2 tasks: It takes the Fourier transform of the reconstruction to produce the correlation and it centers all the correlations independently of which spatial position they originated from (owing to the shift invariance property of the Fourier transform). If the space multiplexed memory is implemented by moving the holographic medium (e.g. disk) then a scanning mechanism is not required in the signal arm. Moreover, the motion of the medium can be used however to implement the relative motion between the reference and signal to restore the 2-D shift invariance that is lost in angle and shift multiplexed memories [13] .

Summary

	Shift invariance	Parallelism	Comments
Angle multiplexing	1-D	>1,000 correlations	Trade-off between shift invariance and the number of correlations
Wavelength multiplexing	2-D	1 correlation sequential access to several thousand	Wavelength scanning is required
Shift multiplexing	1-D	>1,000	Properties similar to angle multiplexing
Phase code multiplexing	1-D	1,000	Associative memory
Peristrophic multiplexing	2-D	>100	Parallel display or sequential scan of the stored holograms through medium rotation
Space multiplexing	1-D or 2-D	>1,000 sequential access to ~100,000 filters	Mechanically scanned medium (disk) or scanned probe beam

Acknowledgements

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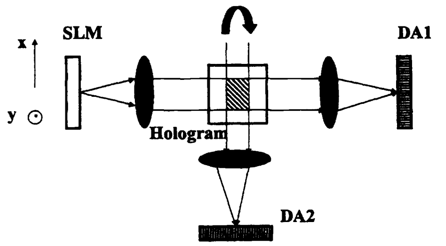

Figure 1. Angle multiplexing

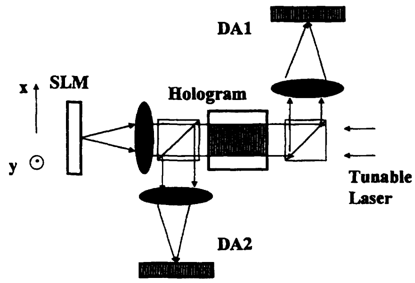

Figure 2. Wavelength multiplexing

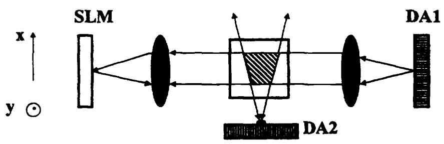

Figure 3. Shift multiplexing

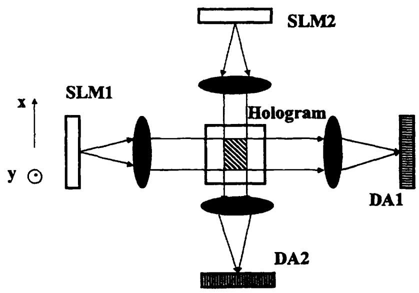

Figure 4. Phase-code multiplexing

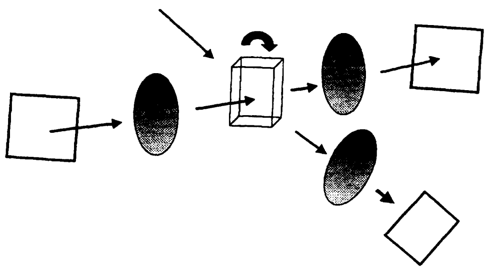

Figure 5. Peristrophic multiplexing

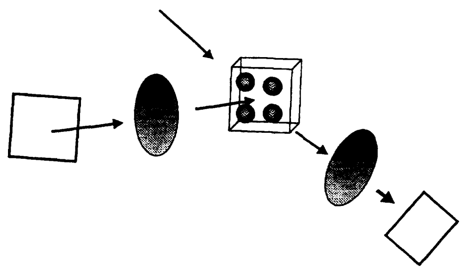

Figure 6. Spatial multiplexing