# Wavelength-multiplexed computer-generated volume holography

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We demonstrate recording and reconstruction of multiple-computer-generated wavelength-multiplexed volume holograms in a holographic storage medium. The holograms display high selectivity, and their reconstruction process results in a convenient conversion of wavelength into angular multiplexing.

Computer-generated holograms (CGH's) are becoming essential components in optical signal-processing schemes. They serve as spatial filters, as optical elements, and as a basic component in interconnection networks. A CGH is a two-dimensional spatial distribution pattern similar to an interference product of two (or more) optical beams. In optical applications, the CGH is usually generated in a computer and electrically transmitted to a spatial light modulator (SLM). A light beam that illuminates the SLM acquires the holographic pattern upon propagation through it. However, all the SLM's are merely planar holograms, and hence the diffraction off them displays multiple diffraction orders that limit the information contents.

Transforming the planar CGH's into volume holograms is desirable for numerous reasons, including increasing the diffraction efficiency and the information capacity and storing multiple holograms. Potential applications are (1) realization of a robust interface between an electronic computer and a volume holographic data storage and (2) storage of artificial data that do not exist as a two- or three-dimensional object (for example, phase-only filters). In the first, the use of CGH's gives a useful degree of freedom that introduces adaptivity[1] in the holographic recording process and enables a user to compensate for imperfections in the recording system (while keeping the desired data unchanged). The second provides a convenient realization of complex filters for image-processing purposes. Moreover, when multiple holograms are stored, it enables multichannel image processing simultaneously. The field of computer-generated volume holography was pioneered by Pugliese and Morris,[2] who stored a single CGH in a photorefractive (PR) crystal. Their results suffered from problems associated with thin holograms,[3] such as multiple orders of diffraction, which were eliminated only at the expense of resolution in the reconstructed data page.

Since a CGH is merely a two-dimensional function, the major problem in transforming it to a volume hologram is its recording in a thick medium with no access to the individual planes of the recording volume. It is obvious, therefore, that incoherent imaging[2] of the CGH from the SLM onto the recording medium cannot solve this deficiency, simply because good visibility of the CGH's fringes is restricted to the focal depth of the linear imaging system.

In this Letter we demonstrate the first experiment, to our knowledge, of multiple storage of CGH's. The CGH's were recorded in a volume holographic storage medium without varying the recording wavelength or any mechanical movements. The planar holographic data are computer generated, transmitted to a SLM, and subsequently converted to volume holograms that display all the advantages of volume holography.[3] Furthermore we suggest a method of speeding up the data-loading process by encoding more than one hologram at a time on the SLM and simultaneously record them in the volume storage medium. Finally, we demonstrate a convenient method for conversion of wavelength-multiplexed holograms into angular multiplexing.

Our experimental setup is shown in Fig. 1. We used a magneto-optic SLM with 128 × 128 pixels. Since it is a binary low-resolution SLM, we find that coding a CGH by the projection-onto-constraint-set algorithm[4] is a rapid and efficient method. This algorithm is an iterative process that transforms a function from one domain to another and vice versa (in our case, from the spatial domain to the spatial-frequency domain). In every domain, the function is projected onto a constraint set. The convergence of the process, if it exists, is achieved when the final function satisfies all the constraints simultaneously. The constraint in the hologram plane (Fourier domain) is such that the CGH transmittance is binary-amplitude modulated. The constraints in the spatial domain are (1) the light distribution obtained at an *a priori* known subarea of the transverse plane is identical to the desired image, and (2) since the CGH is a real function, the conjugate opposite version of

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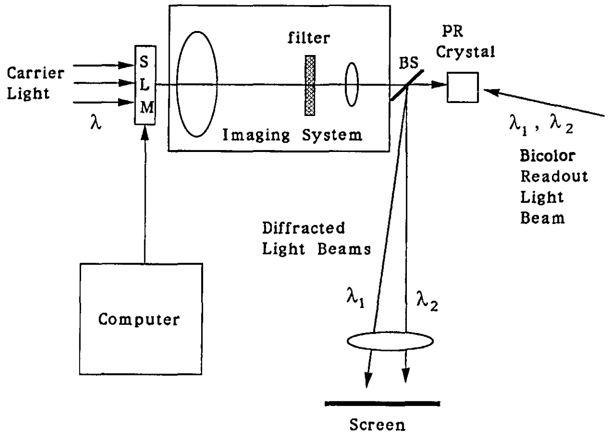


Fig. 1. Experimental setup for computer generation and recording of volume holograms. BS, beam splitter.

the image appears at a region that corresponds to the origin reflection of the subarea.

Let $I(x,y)$ be the intensity distribution of the desired image to be reconstructed from the CGH at a region $S$, located at a distance $d$ from the origin in the transverse (to the optical axis $z$) plane. The constraint set $C_s$ in the spatial domain is $C_s = [h(x,y) : |h(x,y)|^2 = |h^*(-x,-y)|^2 = \gamma I(x,y); x,y \in S]$, where $\gamma$ is a constant and $h(x,y)$ is the Fourier transform of the hologram transmittance $H(u,v)$. The phase distribution of $h(x,y)$ over the whole plane and the amplitude distribution outside the regions $S$ and $-S$ are the degrees of freedom that minimize the error in the reconstruction of the desired image. As for the light distribution outside the regions $S$ and $-S$, we expect a high-intensity peak at the origin, since there always exists a high-bias term in our CGH. However, we neglect all other light distributions in the transverse plane, since, in practice, the intensity inside the region of interest is much larger than the one outside it (except for the origin). Alternatively, the regions outside $S$ and $-S$ can be filtered out by the imaging system that images the CGH onto the volume recording medium. Consequently, we write the Fourier transform of the CGH after filtering as $h(x,y) \cong A\delta(x,y) + f(x-d,y) + f^*(-x-d,-y)$, where $f(x,y) = |f(x,y)|\exp[j\phi(x,y)]$, $\phi$ is a real and random function of $x$ and $y$, and $I(x,y) = |f(x,y)|^2$.

The volume recording medium is a PR crystal that transforms the light-intensity distribution into perturbations in the refractive index. The reconstruction of the data is performed by scattering from the index gratings at their phase-matched (Bragg) angle. Since there is no direct interaction (interference) between the recording and the readout light beams, they can be incoherent to each other. The recording beam can originate from an incoherent source.[2] However, incoherent imaging of the planar hologram from the SLM in the volume recording medium does not transform it into a volume hologram, since the fringes are visible in a range restricted to the focal depth of the imaging system. The immediate consequence is high diffraction efficiency at the expense of resolution or vice versa.[2]

Our method for converting a planar hologram into a volume hologram utilizes the diffraction properties of a coherent image-bearing optical beam. To understand how we convert the two-dimensional CGH to a volume hologram, we realize that when a CGH is illuminated with a coherent beam, each one of the resulting diffraction orders carries the full information contents. If we then interfere any one of these orders, assuming a band-limited signal, with a reference beam, the resulting volume holograms now contain the information. In our case, the interference is between the $-1$ order and the zero order (which plays the role of reference). For example, consider a crude planar CGH, i.e., a simple sinusoidal grating. For a coherent illuminating beam, the far field of the grating consists of two diffraction orders ($-1$ and $+1$), accompanied by a zero order that appears when the fringe modulation in the SLM is not purely bipolar. In principle, interference takes place between each pair of the diffraction orders, but perfectly imaging occurs only when all of them are present. The PR crystal in the image plane therefore converts three interference gratings into index gratings, and three holograms are recorded simultaneously. The hologram formed by interference between the $-1$ and $+1$ diffraction orders is characterized by a wave vector perpendicular to the optical axis and suffers from a short interaction length. The other two holograms, formed between the pairs $\{0,-1\}$ and $\{0,+1\}$ diffraction orders, are tilted with respect to the optical axis and display good visibility over a range that is much larger than the focal depth of the imaging system, strictly because the beams overlap over a larger range. Moreover, the light intensity in the zero order can be designed to increase the fringe visibility further. In the case of a nonsinusoidal grating, additional diffraction orders appear, and one may choose any of these to record the most efficient tilted volume hologram with the zero diffraction order. When the objective is the recording of multiple holograms, elimination of all the redundant gratings is achieved by spatial filtering in the imaging system (see Fig. 1).

For comparison, in the case of incoherent imaging, the only grating that exists is the hologram imaged from the SLM, which has a wave vector perpendicular to the optical axis, and its visibility is limited to the focal depth of the imaging system.[2]

The reconstruction of the stored data is performed by illuminating the PR crystal at the Bragg angle. In a special case where the carrier wavelength is identical to the reconstruction wavelength, the Bragg-matched reconstruction is made with a beam counterpropagating to the $-1$ diffraction order of the recording process, and the readout beam is adjusted to obtain the proper quadratic phase of the carrier beam. The reconstructed image is formed on the optical axis, i.e., counterpropagating with the zero diffraction order. A deviation between the recording and the readout wavelengths yields a change in the Bragg angle of reconstruction. Note that our reconstruction method differs somewhat from conventional holographic reconstructions, since we read out the

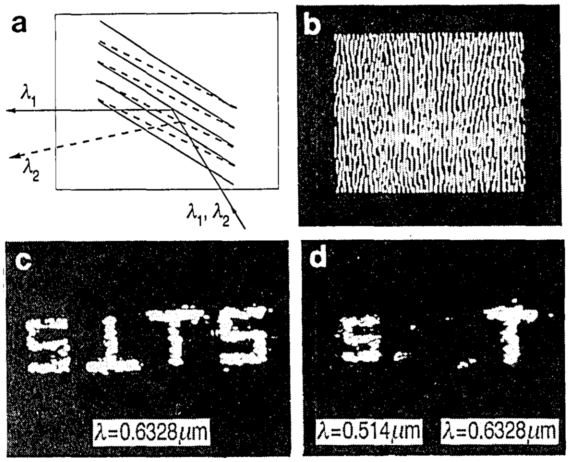


Fig. 2. a, Detailed drawing demonstrating the reconstruction and its angular dependence on the tilted wavelength-multiplexed volume holograms. b, Binary CGH. c, Direct reconstruction from the SLM with an He–Ne laser. d, Reconstructions from the volume holographic medium with the He–Ne and Ar lasers simultaneously. The right image (T) is red, while the left image (S) is green.

data with a beam that propagates counter to the image-bearing beam, and therefore our reconstructed image propagates counter to the direction of the reference beam. This requires that the spatial bandwidth of the readout beam be identical to that of the signal beam (the −1 diffraction orders in our case).

In our experiment we used a red He–Ne laser ($\lambda = 0.6328$ $\mu$m) for recording the hologram and a Gaussian beam with a waist diameter of $2\omega_0 \cong 1$ mm in the PR crystal. We utilize the properties of volume holography by demonstrating simultaneous recording of two wavelength-multiplexed holograms. The original data pages were the letters S and T, and their CGH's were designed to be reconstructed each by a different wavelength: (T by a red He–Ne laser and S by an Ar laser at $\lambda = 0.514$ $\mu$m), from the same angular direction (see Figs. 1 and 2a). The ratio between the periods of the two holograms is calculated from the Bragg condition and Snell's law to be

$$\Lambda_1/\Lambda_0 = [\lambda_0 n(\lambda_1) + \lambda_1 n(\lambda_0)]/2\lambda_0 n(\lambda_0), \qquad (1)$$

where $\lambda_0$ and $\lambda_1$ are the recording and the readout vacuum wavelengths, respectively, and the material's dispersion $n(\lambda)$ is taken into account (we assumed that the zero diffraction order is normal to the crystal surface and all angles are small).

The holograms were superimposed, transmitted to the SLM, and imaged onto the PR crystal ($BaTiO_3$). The imaging system demagnified the CGH to a density of 1280 lines/mm in the crystal, yielding a wavelength selectivity of $\Delta\lambda \cong 0.1$ nm for an interaction length of $L \cong 7$ mm. The reconstruction was performed by the appropriate laser beams, which were incident upon the crystal from the same direction. Since both holograms were converted into the tilted volume holograms during the recording process, each of them acquires a different tilt angle owing to the different periodicity (and hence owing to different angles of propagation for the nonzero diffraction orders). The reconstructed images emerge with an angular separation of 1.4°. Figure 2a shows the diffraction from the tilted volume gratings and demonstrates the dual wavelength and angular separation.

An interesting property of our system is the actual conversion from wavelength to angular multiplexing. In one option the readout consists of a multiwavelength beam, and the reconstructed images are obtained at an angular separation from each other. In an alternative option the readout is performed at one wavelength but from different Bragg angles, and the recovered data are always in the same location (say, on the optical axis). For high-capacity data-storage purposes, however, our system is not optimal, since the angular difference between two adjacent holograms is restricted by their contents. An improved system for high-capacity data storage is currently under study.

The experimental results are shown in Figs. 2b–2d. Figure 2b shows the double CGH, and Fig. 2c shows the direct reconstruction from the SLM with the He–Ne laser only. The SLM acts as a sampler, owing to its binary grid,[5] and by spatial filtering we stored four holograms simultaneously, each yielding one letter of the four located on the right-hand side of the optical axis (see Fig. 2c). Being a thin hologram, the SLM does not possess the wavelength selectivity of a volume hologram, and hence the single-laser readout beam constructed all the images, the first four of which from the left half-plane are shown in Fig. 2c. Figure 2d shows the simultaneous reconstruction from the volume hologram (PR crystal) with the He–Ne and Ar lasers. We reconstructed the images that correspond to the first and the third letters from the left (S and T) of Fig. 2c. The size of the reconstructed images scales as their wavelength.

In conclusion, we have demonstrated a new method for computer generation of volume holograms and employed it for simultaneous computer generation of multiple holograms. We emphasize that our method can be used for storing high-resolution images (or dense data pages) and was practically restricted in our experiment by the resolution of our SLM.

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