Dynamic optical correlation using localized holography

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A new technique for optical correlation using gated holographic recording is demonstrated. Several persistent holograms are localized within separate slices as close as 33 µm apart along the crystal. Individual holograms can be dynamically erased and rerecorded with no need to refresh all other recorded holograms. Experimental results showing the correlation capability, cross talk, shift invariance, and dynamicity of the localized holographic correlator demonstrate unique performance and capabilities for these correlators.

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Optical signal processing and pattern recognition have been appreciated since the complex spatial filtering work by VanderLugt in 1964. The multiplexing advantage of volume holography has made it a significant method to be employed in optical pattern recognition. Most of the holographic correlators are based on the angular multiplexing technique, which can be implemented using a gated holographic recording scheme such as two-center recording in doubly doped LiNbO₃ crystals. By use of gated holography, the recording and erasure of the holograms are possible only in the presence of a gate beam. A simple demonstration of the localized holographic correlator (LHC) is shown in Fig. 1. By shaping the gate beam to form a thin slice within the crystal, the hologram is localized within the volume of that slice [Fig. 1(a)]. The recording beams affect only the sensitized slice and have a negligible effect on other holograms in other slices. Therefore, individual patterns can be dynamically recorded and erased in separate slices of the recording medium. Furthermore, because the absorption of the signal beam as propagating through the crystal is negligible outside the sensitized slice, it is possible to use long crystals to extend the capacity of the LHC. During the correlation phase, the signal beam corresponding to the pattern under investigation propagates through the crystal and is correlated with all the holograms stored in all slices along the crystal. The correlation beams are diffracted toward the detector array right next to the crystal [Fig. 1(b)], with no requirement of a collecting lens after the hologram. This makes the LHC more compact than the conventional holographic correlators. Using theoretical simulations, it is shown that the overall performance of LHCs in terms of cross talk, shift invariance, and capacity is better than that of the conventional correlators.

In this Letter, we present the first experimental results showing the correlation capability, cross talk, shift invariance, and dynamicity of the LHC. Figure 2 is a schematic illustration of the LHC experimental setup. The 532 nm expanded laser beam from a diode-pumped solid-state laser illuminates a spatial light modulator (SLM), which modulates the signal beam with the information of the recorded and correlated patterns in recording and correlation phases, respectively. The DC component of the signal beam is then filtered out at the origin of the Fourier plane of a 4-f imaging system comprising two confocal lenses, F1 and F2. All of the correlated patterns have a DC component. This is caused by the SLM’s being an intensity modulator, producing a nonzero field average for each pattern. Eliminating this common part of the spatial spectrum of the patterns significantly improves the contrast of the correlation process. All the diffraction orders of the SLM, except the zeroth order, are also blocked at the focal plane of lens F1. The magnification ratio of the 4-f system is 1:1.5. The filtered pattern is then Fourier transformed by lens F3 at the entrance facet of the holographic crystal. The focal lengths are chosen to have half of the Fourier transform pattern fit to the crystal width (Lₓ in Fig. 2). This doubles the spatial bandwidth of the system while maintaining the same crystal width.

The reference and the UV gate (wavelength 404 nm) beams are coaligned and are focused by the cylindrical lens CL1 inside the crystal at the same location, where they form two overlapping slices of light that define the recording slice. Before merging of these two copropagating beams, they are filtered and shaped like one-dimensional Gaussian beams by two separate sets of confocal cylindrical lenses [(CL2, CL3) for the reference and (CL4, CL5) for the UV] and slits. The slits remove the fringes that would appear around the main light slice. This significantly reduces the cross talk between adjacent slices. Also, the holograms can be selectively recorded and erased.
within select slices without erasing neighboring holograms. The beam waist diameters \((2w_0)\) of the reference and UV Gaussian beams are 18 \(\mu m\). The full width of the UV beam within the crystal defines the slice thickness. The waist of the UV beam occurs in the center of the entrance and exit facets of the crystal. The waist of the reference beam is located at the exit facet of the crystal, where the detector array is planned to be attached (or placed in close proximity). The location of the two overlapping beams (i.e., reference and UV) along the crystal is controlled by a precision translation stage, which shifts the focusing cylindrical lens CL1. For simplicity, in all the demonstrations of the LHC in this Letter the distance between the adjacent slices is the smallest reported to date for localized holography. To study the cross talk in LHCS, we used the experimental setup in Fig. 2 to record localized holograms of random patterns in seven slices 33 \(\mu m\) apart from each other. Comparing the 33 \(\mu m\) slice distances with the width of the holograms (about 18 \(\mu m\)) it is notable that we have added a buffer space between adjacent holograms to reduce cross talk. To the best of our knowledge, the 33 \(\mu m\) distance between the adjacent slices is the smallest reported to date for localized holography. To study the cross talk in the worst case scenario, we left the center slice blank (i.e., no hologram recorded) and used the same pattern for all the other six holograms. The holograms were then read by the same pattern used for recording. The diffracted signals at all seven slices are shown in Fig. 3(a). Because there is no hologram recorded within the gap at the center slice in Fig. 3(a), the power collected at this slice is initiated from the tails of the diffraction profiles of the neighboring holograms and small scatterings, which is defined as cross talk. Figure 3(a) clearly shows the negligible cross talk in LHCS. The cross-talk noise-to-signal ratio (NSR), which is the ratio of the power at the location of the missing hologram to that at the adjacent peaks, is about −20 dB. We repeated the above experiment with the same pattern used for six holograms, but instead of leaving the center slice blank, we used a different random pattern for recording a hologram there. The holograms were then read by the same pattern used for recording the six surrounding holograms. The diffracted signals at all the seven slices are shown in Fig. 3(b). The collected power at the middle slice represents the cross-correlation of the reading pattern and that used for recording of the middle hologram plus the cross talk caused by diffraction from adjacent holograms at the middle slice. Comparing Figs. 3(a) and 3(b), it is observed that the amount of power at the location of the unmatched hologram [in the middle slice in Fig. 3(b)] is about the same as that at the location of the blank slice [in the middle slice in Fig. 3(a)]. One can conclude that the system does the cross-correlation well with good discrimination. It is notable in Fig. 3 that the strength of the six holograms is decreasing from left to right. The holograms have been recorded in order from right to left. During recording of each hologram, the signal beam reads previously recorded holograms, which partially erases them. Partial loss of persistence while reading with green light explains this effect. Instead of equal recording times for all of the holograms, a schedule can be calculated for the recording times based on the recording and erasure time constants, which results in equal strengths of the recorded holograms.
5 min for the right-side hologram (first recorded), shown in Fig. 5(a). The recording times varied from read by the same pattern. The diffracted signals are with the same pattern. The holograms were then investigate this effect, we recorded seven holograms dynamic modification of the pattern database. To in-
z-axis (directed along the plane shift, because of the asymmetry of the grating curves show asymmetry in the response to the in-

Another important property of any correlator is shift invariance, which is defined as the minimum amount of the lateral shift of the matched reading pattern required to reduce the diffraction efficiency to zero.3 To study the shift invariance of the LHC, one hologram was recorded in one slice. The hologram was then read by the same pattern used for recording but the pattern was shifted by different amounts on the SLM. The in-plane shift was applied (i.e., in the x-direction in Fig. 2). The diffraction efficiency was measured per each shift value. Figure 4 shows the diffraction efficiency, normalized to the diffraction ef-

A unique advantage of the LHC is the possibility of dynamic modification of the pattern database. To in-
vestigate this effect, we recorded seven holograms with the same pattern. The holograms were then read by the same pattern. The diffracted signals are shown in Fig. 5(a). The recording times varied from 15 min for the right-side hologram (first recorded), exponentially reduced from one slice to another, to 2 min for the left-side one (last recorded) with no presensitizing phase. We then erased the middle holo-
gram by illuminating the middle slice with the UV beam and the reference beam for 20 min without changing their intensities. After erasure, the holo-
grams were read by the recording pattern, and the diffracted signal is shown in Fig. 5(b). The erasure time was selected properly so that the diffraction ef-

Fig. 4. (Color online) Shift invariance of the LHC, simulation and experiment. The in-plane shift (in the x-direction in Fig. 2) is applied. The horizontal axis corresponds to the shift of the magnified pattern behind lens F2 in Fig. 2. The pixel pitch of the magnified pattern is 42 μm.

Fig. 5. Dynamic recording/erasure in LHC. (a) Seven holograms are recorded in order from right to left. (b) The hologram at the center is erased by illuminating it with the UV and reference beams, and (c) the hologram at the center is rerecorded for 2 min. The recording and reading intensities are the same as those mentioned in the caption of Fig. 3.

References