Shift-invariant real-time edge-enhanced VanderLugt correlator using video-rate compatible photorefractive polymer

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We demonstrated a real-time shift-invariant VanderLugt correlator (VLC). The VLC was implemented with a 37 μm thick *bis*-triarylamine side-chain polymer matrix photorefractive (PR) polymer composite operating at 532 nm wavelength. Correlation selectivity was enhanced by real-time edge enhancement. The advantage of the VLC is that its architecture allows overcoming the PR material response speed. A correlator of this type enables a fast shift-invariant search of a large optical image database. A high degree of shift invariance in our correlator was possible because of the material thickness. The angular bandwidth of this material was measured experimentally in a degenerate four-wave mixing setup, and it was found to be in a very good agreement with the theory. © 2006 Optical Society of America

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Optical data storage continues to attract significant interest because it offers the possibility of creating large image databases that can be searched at a high speed because of the parallelism in optics. A massive optical memory system can be realized by dense holographic storage achievable with multiplexing techniques, of which spatio-angular multiplexing (SAM) is the most straightforward and effective one.[1–5] The superparallel holographic ROM (SPHROM) is the architecture proposed by our group to implement dense SAM with fast retrieval, capable of storing up to 2 Tbytes of data.[3–5] Search of the holographic memory is typically accomplished with a shift-invariant Fourier transform (FT) based correlator.[6] The two types of simple correlator are the joint transform (JTC) and the matched spatial filter or VanderLugt (VLC) correlators, either of which can be implemented in real time by degenerate four wave mixing in a photorefractive material.[7,8] Physical implementation of any mathematically shift-invariant correlator requires that the holographic material possesses sufficient angular bandwidth. This requirement can be fulfilled by using a thin photorefractive (PR) material.

The diagram in Fig. 1 shows our proposed system, consisting of the SPHROM coupled with a shift-invariant real-time VLC. The correlation is performed in the VLC architecture to achieve a much higher image recognition system operational speed than what a JTC architecture would allow.[8,9] The PR grating is written by the FT of the query image and a reference plane wave at the speed limited by the response of the PR material. However, once the grating for a particular query image has been written, the rest of the searching process happens at the speed with which the probe beam, carrying the FT of the images retrieved from the SPHROM, diffracts from the grating.

In this paper we demonstrate two-dimensional (horizontal and vertical) shift-invariant correlation[10] using recently invented *bis*-triarylamine side-chain polymer matrix,[11–13] 37 μm thick PR polymer composites operating at 532 nm. The gratings in our experiment were written by beams intersecting in the horizontal plane. The material samples for our experiment were provided by Nitto Denko Technical Corporation (NDT). We consider this PR polymer material to be the prime candidate for the implementation of a shift-invariant search of the SPHROM, because this material has a demonstrated capability of stable dynamic video-rate operation and a long shelf lifetime at room tempera-

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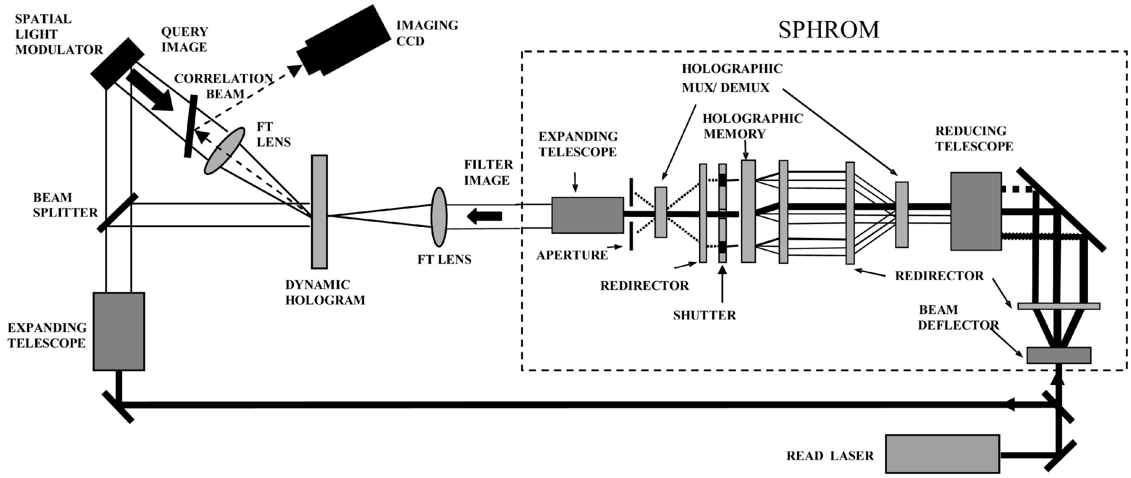

Fig. 1. Real-time VLC coupled with SPHROM.

ture.[11] A previously reported PR polymer VLC was constructed from poly(*N*-vinyl carbazole) (PVK)-based PR polymer,[9] a material in which deterioration of PR properties was observed after prolonged use.[10] In addition, the experiment reported in Ref. 9 relied on a cross-hairs filter to perform edge-enhanced correlation. In our experiment, edge enhancement was achieved in real time by adjusting the intensities of the writing beams.[14,15] Our experiment was performed with a PR polymer sample with a large transverse area of 1.5 in. in diameter, using an ND:YAG frequency-doubled solid-state pumped Verdi laser, operating at 532 nm. VLC filter images were stored in photopolymer-based Memplex thick holographic material,[16] developed by Laser Photonics Technology, Inc. This material can have a large $M/\#$ (>20), and holograms written in this material can survive at room temperature for many years without noticeable degradation.

Prior to the correlation experiment, we measured the angular bandwidth of the PR polymer sample by performing incoherent phase conjugation readout in a degenerate four-wave mixing configuration. The diagram illustrating the experimental setup is presented in Fig. 2. The sample consisted of the PR polymer composite with an average refractive index $n_0 = 1.6$ sandwiched between indium tin oxide (ITO) electrode-coated glass plates. An external DC field was applied across the sample. We determined experimentally that the maximum diffraction efficiency was obtained at a 3 kV bias. The grating was written by two *s*-polarized, collimated Gaussian beams A_1 and A_2, incident on the hologram at 60° and 30° to normal in the air, respectively. The writing beams

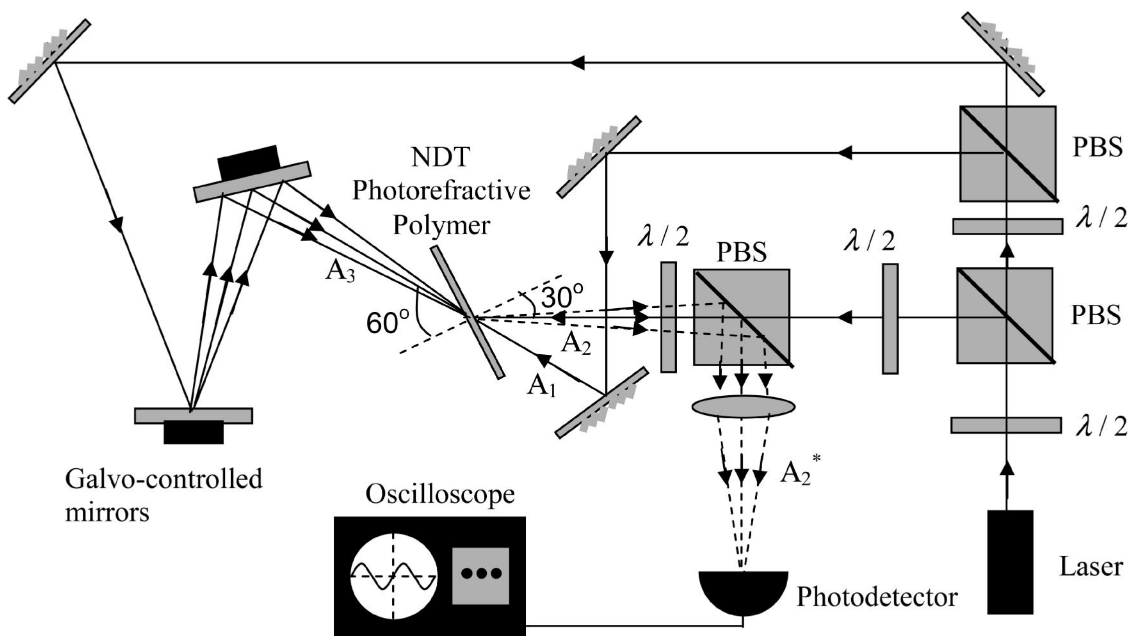

Fig. 2. Experimental setup for measuring the angular bandwidth of the PR polymer sample.

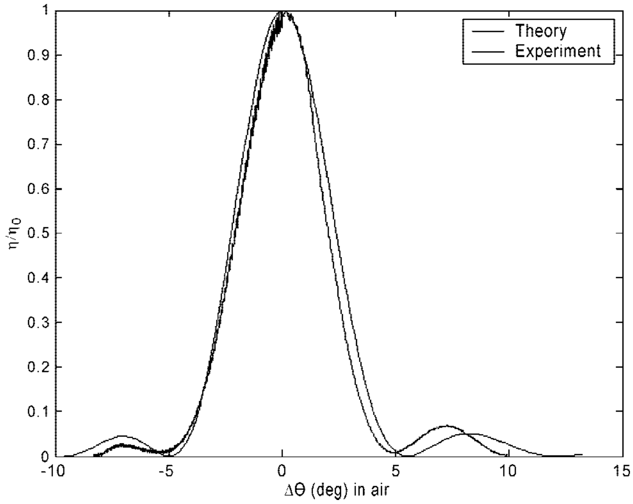

Fig. 3. Experimentally measured angular bandwidth for the PR polymer sample, along with the coupled-wave theory curve.

were each 5 mW in power, with spot diameters of 5 mm. Because of the Fresnel refraction in glass, the actual angles of incidence of the beams A_1 and A_2 in the material were 35° and 20°, respectively. An asymmetric writing beams arrangement was needed so that the gratings **K** vector would make an angle with the poling field direction. The *p*-polarized probe beam A_3 at 2 mW power with a 5 mm spot size was incident on the grating, aligned to be exactly counterpropagating to the writing beam A_1. The phase-conjugated beam $A_2{}^*$ was reconstructed with *p* polarization. A diffraction efficiency of about 1% was observed (when reading the grating with a He–Ne laser at 633 nm, a diffraction efficiency close to 40% was observed). After passing through the half-wave plate, $A_2{}^*$ became *s* polarized, and subsequently it was reflected by the polarizing beam splitter (PBS) cube. Note that all the PBS cubes mentioned in this paper transmit *p*-polarized beams and reflect *s*-polarized beams.

In order to measure the angular bandwidth of the PR polymer sample, the probe beam was scanned with the help of computer-controlled galvo mirrors (see Fig. 2). The two-mirror galvo system, sweeping at an average rate of 15 rad/s, was designed to keep the probe beam at a fixed spot on the hologram, while changing the angle of incidence. Since the beam $A_2{}^*$ was also sweeping through a large angle, a 2-*f* to 2-*f* single-lens imaging system was set up to keep $A_2{}^*$ on the detector. The signal was detected with a Thorlabs PDA55 10 MHz bandwidth photodetector. One can see from Fig. 3 that the angular bandwidth in the air measured between the first nulls of the sinc function for our sample is about ten degrees. The slight disagreement between theoretical and experimental data can be attributed to several factors. One is that the probe beam has the same wavelength as the writing beams, so that the gratings were being partially erased during the readout. This in turn affects the angular bandwidth of the diffraction process. Another factor is the presence of possible imperfections in the scanning galvo mirrors system alignment, which could result in wanderings of the probe beam from the desired spot. Other factors could include system hardware stiction and backlash.

The theory plot was obtained from the coupled-wave equations for lossless transmission dielectric

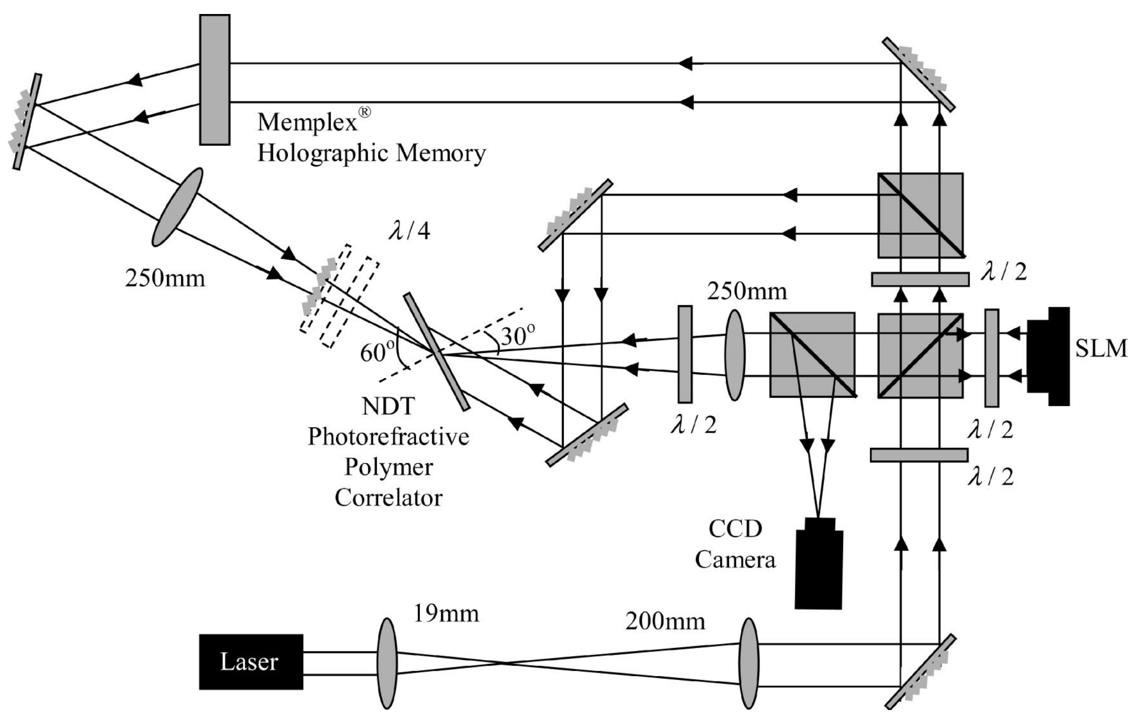

Fig. 4. Experimental setup for demonstrating the shift-invariant real-time VLC.

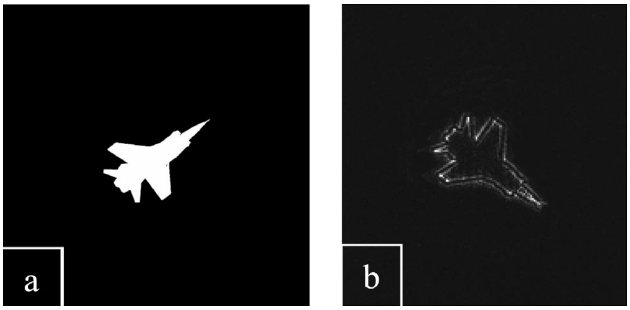

Fig. 5. (a) SLM image. (b) Edge enhanced phase-conjugated reconstruction of the SLM image.

gratings.[17] Since the range of angular deviations from the Bragg angle was quite large during the experiment, we did not follow the usual approach of Taylor series expansion in the small parameter $\Delta\theta$. Instead, all the relevant parameters were recalculated using the defining equations each time the incident angle was changed. Under the stated experimental conditions, we observed Bragg diffraction. To confirm that diffraction in our samples was in the Bragg regime, we calculated the values of $Q = 2\pi\lambda d/n_0\Lambda^2$ (Klein–Cook) and $\rho = \lambda^2/\Lambda^2 n_0 n_1$ (Raman–Nath) parameters.[18,19] Here d is the sample thickness, n_1 is the amplitude of the refractive index modulation, and Λ is the grating periodicity. We determined that $n_1 \approx 3 \times 10^{-4}$ by measuring the diffraction efficiency at the Bragg angle. We obtained $Q \approx 36$ and $\rho \approx 300$, which satisfy the conditions for the Bragg regime that both $Q \gg 1$ (thick grating) and $\rho \gg 1$ (weak modulation).

The diagram detailing the experimental setup of the shift-invariant VLC demonstration is shown in Fig. 4. Expanded laser beams with spot sizes of 1 in. diameter were used in the correlation experiment. The query image of a MIG-25 jet [Fig. 5(a)] was encoded on the expanded laser beam with the help of a Boulder Nonlinear Systems 512×512 pixel reflective ferroelectric-liquid-crystal spatial light modulator (FLC SLM) with a pixel size 15×15 μm. The filter image of a MIG-25 jet was retrieved from the Memplex holographic memory. A CCD capture of the retrieved image is shown in Figs. 6(a) and 7(a). A real-time grating in the PR polymer was written with an s-polarized FT query image beam and an s-polarized plane wave. The probe beam carrying the FT of the filter image was p polarized. The writing beams carried about 5 mW of optical power each, while the probe beam was about 0.5 mW. A quarter-wave plate and the mirror shown in the diagram in Fig. 4 by dashed lines were installed on flip mounts. The purpose of these two components was to monitor the power ratio of the signal and reference beams in order to produce an edge-enhanced hologram. This technique is based on the fact that most optical power of a typical image spectrum resides in the low frequencies. If the intensity of high frequencies matches the intensity of the reference beam, the intensity of the DC component significantly exceeds the intensity of the reference. Hence, the modulation depth (m) of the DC part of the spectrum is low, and the DC is not recorded well in the hologram.[13] DC suppression could be observed in real time by retroreflecting the reference beam with the flipping mirror through the quarter-wave plate. Double passing of

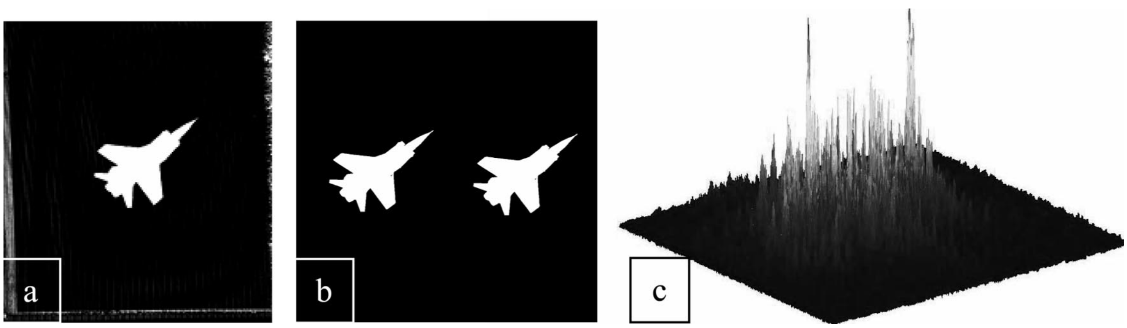

Fig. 6. Horizontal shift: (a) Memplex image, (b) SLM image, (c) correlation.

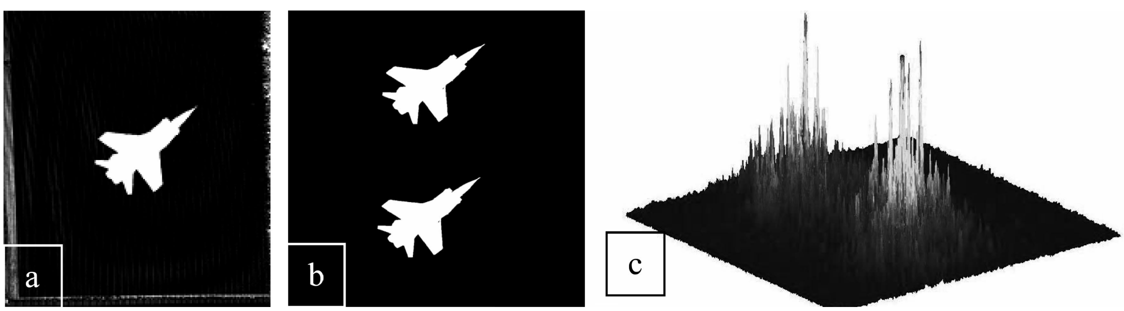

Fig. 7. Vertical shift: (a) Memplex image, (b) SLM image, (c) correlation.

the s-polarized reference beam through the quarter-wave plate resulted in converting it to a p-polarized beam. The retroreflected reference, now acting as a probe beam, diffracted from the grating, producing a phase-conjugated beam carrying an edge-enhanced image that could be observed with a CCD camera. A CCD capture of the edge-enhanced SLM query image is shown in Fig. 5(b). The image appears inverted with respect to the original because the phase-conjugating system acts as a 4-f system. In our experiment the SLM query image was edge enhanced; however, for a practical system a better alternative might be to store edge-enhanced images in the large optical memory database.

Once the desired level of edge-enhancement was achieved, the quarter-wave plate and the mirror were lowered so that the cross-correlation signal could be observed on the CCD camera. The CCD capture of the probe beam is shown in Figs. 6(a) and 7(a). We demonstrated shift invariance of correlation by projecting query images consisting of two MIG-25 jets, horizontally translated to the left and to the right by about 100 pixels from the center in the SLM frame [Fig. 6(b)]. In the experimental setup with a 250 mm FT lens, this shift corresponded to $|\Delta\theta| = 0.34°$ angular deviation from the Bragg angle of the DC part of the image. The correlation signal is shown in Fig. 6(c). Vertical displacement of the image by 100 pixels up and down in the SLM plane is shown in Fig. 7(b), and the corresponding correlation signal is shown in Fig. 7(c). We observed a considerable amount of speckle noise in the correlation, possibly because of scattering in the PR polymer. Nevertheless, the correlation signal from the PR polymer could be thresholded to produce an unambiguous spot identifying the location of the query image.

It should be noted that the spatial frequency components in the Fourier plane of the probe beam might be distributed over a large area, depending on the features of the image, the beam diameter, and the focal length of the FT lens. For example, the Fourier spectrum of the MIG-25 jet image obtained from a 100×150 pixels size SLM image with a 250 mm lens covers an area of about 4 mm in diameter. The real-time VLC architecture is quasi phase matched because only the mean $\mathbf{k}$ vector of the probe beam (essentially only the DC part of the spectrum) is counterpropagating to the reference beam. Higher spatial frequencies that carry the information about the image contours are incident at Bragg-mismatched angles. Thus, the high spatial frequencies will not diffract from the grating unless their angle of incidence is within the allowed angular bandwidth. Therefore, it is advantageous to have a real-time material that is both thin and has a large aperture to capture the entire Fourier spectrum of an image, such as the material that we used.

In summary, we have demonstrated a real-time shift-invariant VLC with real-time edge enhancement. The VLC was implemented with a 37 μm thick triarylamine-based PR polymer composite operating at 532 nm wavelength. A high degree of shift invariance in this material is possible because of the material thinness. Large values of the Q and ρ parameters indicate that coupled-wave theory is applicable to describing the diffraction process in this material. The angular bandwidth of this material was measured experimentally in a degenerate four-wave mixing setup. The experimental data agree with coupled-wave theory results.

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