Optical computing by use of photorefractive polymers

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A matched-filter four-wave-mixing optical correlator was built with a photorefractive polymer as the nonlinear material. Two different time scales are important for this type of device: the time to write a grating, which is limited by the response time of the photorefractive material (~100 ms for the polymer used) and the time to diffract light from the grating, which is essentially instantaneous. For the matched-filter optical correlator we have obtained correlations comparing two 5000-pixel images, using 220-fs pulses with 5-mW average power, demonstrating that the time to compare the test image and the reference image is not limited by the relatively slow response time of the photorefractive polymer. Since the photorefractive grating is erasable the device can be reprogrammed for a different reference image in less than 1 s. The results show that photorefractive polymers can be used efficiently in optical image processing applications.

Four-wave mixing can be used to implement several different computing functions, including correlation,[1,2] optical interconnects,[3] matrix addition,[4] and associative memory.[5] Photorefractive (PR) materials are among the best candidates for the recording medium for such applications because of their high sensitivity and because the recording is erasable in these materials. Moreover, large diffraction efficiencies are achievable at relatively low light intensities. However, until recently the choice of the PR materials was almost exclusively confined to inorganic electro-optic crystals (such as lithium niobate or barium titanate). Such crystals are costly to grow, their PR properties vary from crystal to crystal, and they require a fairly powerful laser source (such as an argon-ion laser) as the pump. All these considerations made devices based on the PR crystals rather impractical.

The recent development of PR polymers with diffraction efficiencies that approach unity[6] (with a low-power laser diode used as the pump) implies that the practicality of four-wave-mixing PR devices should be reconsidered. PR polymers are inexpensive and easy to process. The high diffraction efficiencies originate from light-induced index changes as large as 10^{-2}.[6]

A frequent criticism of devices based on PR materials concerns the slow speed of the photorefractive effect, a criticism that is only partly justified. Although the time to write a grating in a PR material is limited by the need to physically move charge carriers over distances comparable with the wavelength of light, the time required for diffraction of light from the induced grating is on a subfemtosecond scale. This has important implications for device designers. By using the responses at the two relevant time scales efficiently one can carry out useful optical computing functions with PR materials even in the femtosecond time regime.

Optical correlation of entire images can be done by means of four-wave mixing with spatially modulated beams. Two different correlator architectures are possible, i.e., the matched-filter and the joint-transform architectures.[7] The joint-transform correlator uses the two spatially modulated beams to form an interference grating and an unmodulated beam to diffract from the grating; the correlation operation cannot be completed until the grating is formed, typically requiring times (for PR materials) that range from microseconds to seconds. In contrast, the matched-filter correlator uses one spatially modulated beam and one unmodulated beam to form the grating; the other spatially modulated beam diffracts from the grating. If in a matched-filter correlator the spatially modulated beam that forms the grating is used to carry the reference image, and the beam that diffracts from the grating contains the data images (equivalent to the database of images to be searched), then fast searches of image databases are possible, with the proviso that starting a new search requires a relatively long reconfiguration time equivalent to the grating formation time.

A diagram of the matched-filter image correlator is shown in Fig. 1. The pump beam was expanded to a 25-mm diameter and then split into an object beam (ob), a reference beam (ref), and a read beam (re). The object beam and the reference beam (writing beams) had equal path lengths. The object beam and reading beam were intensity modulated with optically addressed nematic liquid-crystal spatial light modulators (SLM's; Micro-Optics P2010) and then Fourier transformed by lenses focused onto the PR film. The reference beam was reduced to a 2-mm diameter and collimated. All beams were *s* polarized on the PR sample. The reference and the reading beams counterpropagated, creating a phase-matching condition that constrained the phase-conjugate beam so that

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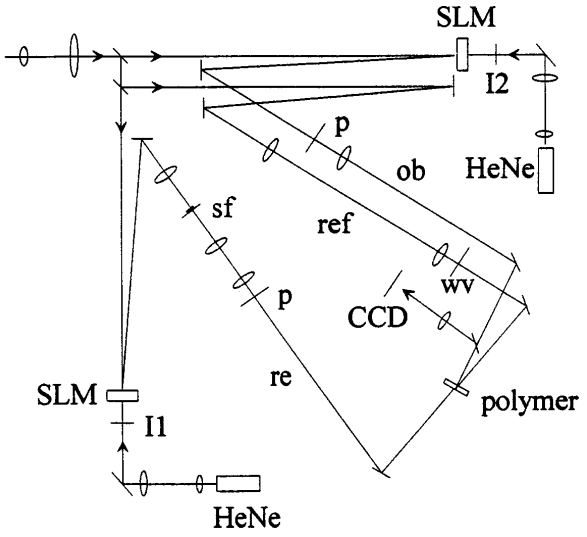

Fig. 1. Schematic of the optical correlator. HeNe's, helium–neon lasers; I1, I2, slides containing the test and the reference images, respectively; sf, spatial filter; p's, polarizers; wv, wave plate.

it emerged counterpropagating to the object beam. The phase-conjugate beam was then picked off by a beam splitter. The amplitude of the phase-conjugate beam was $A_{pc} \cong A_{ref}A_{re}A_{ob}{}^{*}$. Since the reference beam was collimated and therefore contained no spatial information the amplitude of the phase-conjugate beam was proportional to $A_{re}A_{ob}{}^{*}$, equivalent to the cross correlation of the two-dimensional images placed into the read and object beams by the SLM's. The phase-conjugate beam was then inverse Fourier transformed by a lens and imaged by a CCD array. A spatial filter (a 20-μm-diameter metal dot placed at the focal point of a lens in the read beam) was used to improve the correlation by removal of the lowest spatial frequencies.

The correlator was pumped by a femtosecond laser system consisting of a colliding-pulse mode-locked dye laser pumped by an argon-ion laser, which was amplified by a doubled Nd:YLF-pumped bow-tie amplifier. The resulting pulse stream consisted of 220-fs pulses at 1-kHz repetition rates with a 630-nm wavelength and an average power of 5 mW (pulse energy of 5 μJ). The correlator was equipped with delay lines to permit femtosecond operation.

A guest–host PR polymer was used consisting of 2,5-dimethyl-4-(*p*-nitrophenylazo)anisole (DMNPAA), poly(*N*-vinylcarbazole) (PVK), *N*-ethylcarbazole, and 2,4,7-trinitro-9-fluorenone (TNF); 50:33:16:1 wt.%. Films of 105-μm thickness were sandwiched between two transparent electrodes. An electric field of 6 kV (57 V/μm) was applied to align the permanent dipoles of the nonlinear-optical chromophores (DMNPAA) and thus break the inversion symmetry to permit observation of a macroscopic electro-optic effect (poling). In order to have some component of the external field along the grating wave vector **K** we performed the experiments in a tilted geometry (tilt angle of 45°). Because of the low glass-transition temperature of this material the poling is performed at room temperature. In all the experiments reported here the external poling field was applied continuously during the four-wave mixing.

The optical quality of the polymer films was good enough to ensure minimal scattering from the samples. The maximum diffraction efficiency that can be achieved with this PR polymer at 57 V/mm is determined by the experimental geometry, the power density of the writing beams, and the operating wavelength. Under certain conditions diffraction efficiencies as high as 86% were observed with this material at 675 nm.[6] Under the experimental conditions described here the diffraction efficiency was ~15%. The absorption coefficient in the PR material was ~15%. The absorption coefficient in the PR material was ~20 cm^{-1} at 630 nm, which is in the tail of the PVK:TNF charge-transfer complex absorption curve.[8]

The operation of the correlator is demonstrated in Plate I. Plate I(a) is the reference image, a square, and Plate I(b) is the data field that is searched, consisting of two squares, a triangle, and an X. Plate I(c) is a three-dimensional plot of the correlation, in which the peak height corresponds to the intensity of the correlation signal. The two squares generate the largest correlation signal, and the X generates the smallest signal; the triangle is intermediate, resembling the square in overall size but having a different shape. The signal-to-noise ratio is greater than 10:1.

We measured the temporal autocorrelation of both the incident reading pulse and the diffracted pulse. Both pulse widths were the same, as one might expect, and equal to 220 fs, demonstrating that correlations are completed on the femtosecond time scale.

We measured the spatial resolution of the correlator by collimating the object beam and modulating the reading beam with a standard U.S. Air Force 1951 resolution target. The resolution was 1.6 line pairs/mm over the 25-mm SLM aperture, equivalent to 5000 pixels of information. Note that the resolution of the polymer itself is not the limiting factor in the overall spatial resolution of the device. It is sufficient to permit writing of excellent-quality holographic phase gratings with a grating spacing down to at least 1 mm.

The peak information-processing capability of the PR correlator is limited by the SLM reconfiguration time (~30 ms) and the response time of the detection system. Even with the rather slow response of the SLM's, the correlator is capable of comparing two 5000-pixel images every 30 ms and is ready for a new reference image in less than 1 s (with the PR polymer that we used).

Because the response time of the PR polymer is ~100 ms (for a power density of the writing beams greater than 1 W/cm^2), no fewer than 100 pulses are needed at the 1-kHz repetition rate to write a grating. Taking into account the low writing beam power density used in the correlator, we see that the response time becomes even longer and approaches 1 s. Therefore mechanical vibrations become an important issue in the performance of the correlator, affecting mostly the amplitude of the signal. The slight pulse-to-pulse pointing instability of the ampli-

fied colliding-pulse mode-locked laser could also degrade the correlation.

We have demonstrated the use of a PR polymer with very high diffraction efficiency in a matched-filter optical correlator. The device is capable of comparing 5000-pixel test images with a reference image, with the rate limited by only the reconfiguration time of the SLM's and the response time of the detection system. This and the ability to be reprogrammed for a new reference image in less than 1 s (in the current system) makes PR-polymer-based correlators suitable for many image processing applications. The low cost and the good processibility of PR polymers make them especially attractive for applications.

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References

1. J. O. White and A. Yariv, Appl. Phys. Lett. **37,** 5 (1980).
2. G. Gheen and L. J. Cheng, Appl. Opt. **27,** 2756 (1988).
3. P. Yeh, A. E. T. Chiou, and J. Hong, Appl. Opt. **27,** 2093 (1988).
4. P. Yeh, S. Campbell, and S. Zhou, Opt. Lett. **18,** 903 (1993).
5. E. G. Paek and D. Psaltis, Opt. Eng. **26,** 428 (1985).
6. K. Meerholz, B. Volodin, Sandalphon, B. Kippelen, and N. Peyghambarian, submitted to Nature (London).
7. P. D. Foote, T. J. Hall, and L. M. Connors, Opt. Laser Technol. **2,** 39 (1986).
8. G. Weiser, J. Appl. Phys. **43,** 5028 (1972).

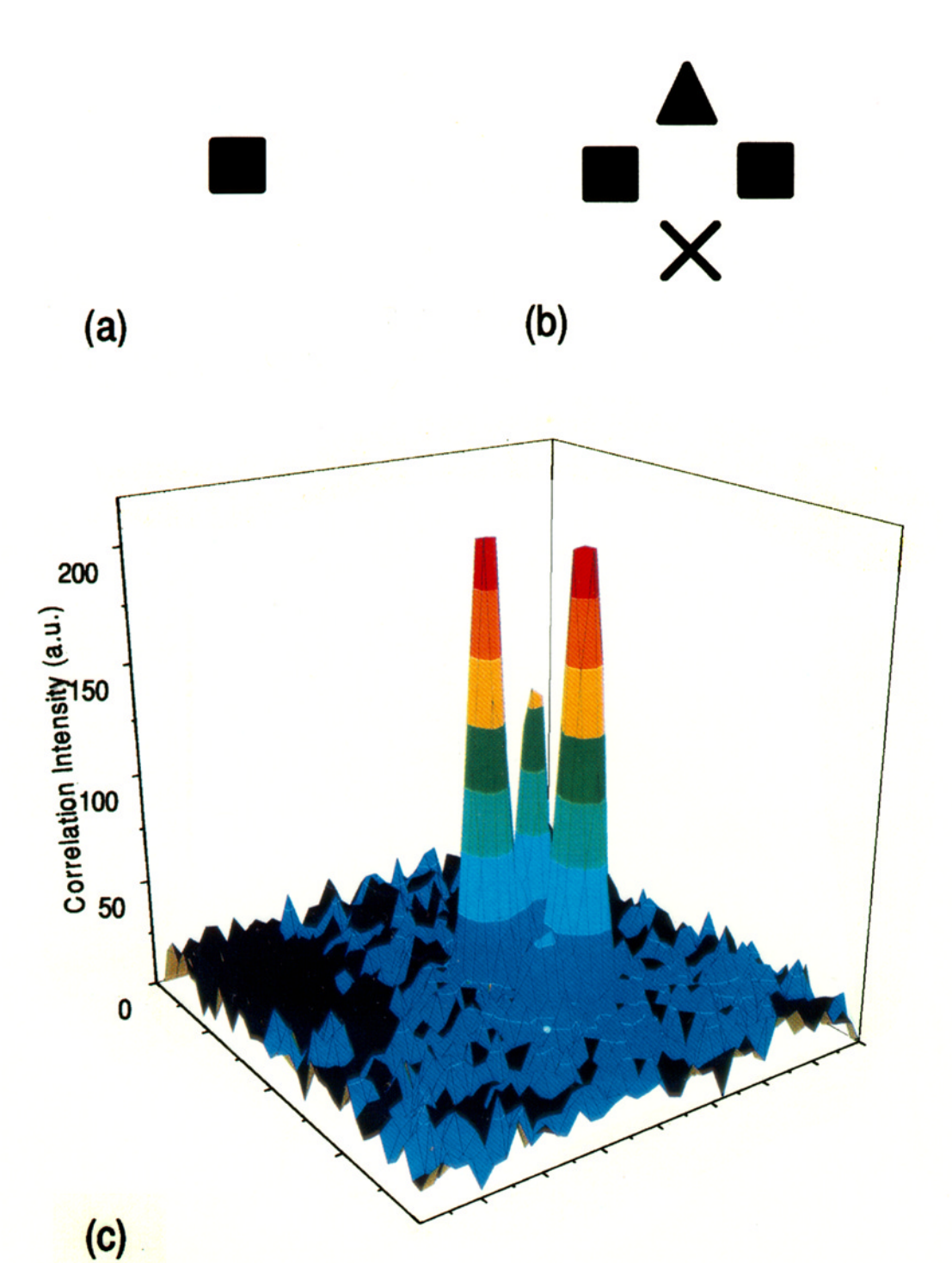

Plate I. (a) Reference image, (b) database of images to be searched, (c) correlation of the images in (a) and (b). The two large peaks are the correlation intensities between identical images of a square.