Optical information processing with the double phase conjugate mirror

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Abstract. The operation of the double phase conjugate mirror (DPCM) is described. It can be regarded as a bidirectional spatial light modulator and controllable filter. Two independent image-bearing beams that may be derived from different lasers exchange their spatial information as they are coupled into each other in a photorefractive crystal. The DPCM is also shown to be an optical thresholder and spatial filtering device, displaying edge enhancement. We propose the use of a resonator with two facing DPCMs to implement iterative image processing algorithms.

Subject terms: optical information processing; photorefractive materials; spatial light modulation; optical thresholding; edge enhancement; iterative image processing algorithms; optical phase conjugation.

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CONTENTS

1. INTRODUCTION

Real-time optical information processing using photorefractive materials has received much attention over the past few years. Some of the applications suggested utilize two-wave-mixing (2WM) configurations.[1] Other applications are based on a four-wave-mixing (4WM) process in the crystal.[2–6]

In recent papers we described the operation of the double phase conjugate mirror (DPCM), which is a 4WM configuration, and discussed various applications in image processing, interferometry, and laser locking.[7–9] In this paper we describe in further detail the characteristics of the DPCM that set it apart from other photorefractive phase conjugate mirrors. In particular, we describe its operation as a new type of spatial light modulator and controllable filter, where information-bearing beams originating from the same or different lasers spatially modulate each other by totally exchanging their spatial information. This occurs without information crosstalk. A theoretical analysis shows that the DPCM can act as a thresholding element. We make use of this property to demonstrate edge enhancement with the DPCM. Finally, we suggest the implementation of iterative processing algorithms using two facing DPCMs.

2. SPATIAL LIGHT MODULATION AND CONTROLLABLE FILTERING

The DPCM is shown schematically in Fig. 1. Two input beams, 2 and 4, are incident onto opposite sides of a photorefractive crystal. Each input beam i may carry different spatial information A_i. These inputs are coupled and self-refracted into each other through a dynamic 4WM process, in which phase gratings develop within the region of intersection of these two input beams. The gratings are written by beam 2 with the self-refracted beam 3, and simultaneously by beam 4 with the self-refracted beam 1. Owing to this grating formation and beam refraction, part of beam 2 loses its spatial information as it is channeled and bent into output beam 3, which now carries the phase conjugate information of input 4. Simultaneously, a portion of input 4 is processed in the opposite direction, so that its own spatial information is replaced by the phase conjugate information of input 2 as it is bent into output beam 1. Since beam 2 writes the gratings with a portion of itself (beam 3), and similarly beam 4 writes the same gratings with a portion of itself (beam 1), these input beams need not be mutually coherent and may even be derived from separate lasers,[8] as shown in the figure. The only restriction for phase conjugation is on the maximum difference in wavelengths $\Delta\lambda$ of the two inputs, which is dictated by the Bragg selectivity of the volume gratings: $(\Delta\lambda/\lambda) \leq (\Lambda_g/\ell)f$, where Λ_g is the grating period, ℓ is the interaction length in the crystal, and f is a geometric factor for the slanted gratings. For typical values of $\Lambda_g \sim 2$ μm and $\ell \sim 1$ mm, $\Delta\lambda \lesssim 1$ nm.

According to the above explanation, the DPCM is actually a new type of bidirectional spatial light modulator. Two independent spatially complex light beams exchange spatial information as they are guided into a counterpropagating light channel through the crystal. This idea is shown schematically in Fig. 2. It is also a controllable filter, since any laser beam can be spatially modulated by a signal beam from another "local" laser source. We have made use of this novel filter to demonstrate beam cleanup, beam combining, and laser locking,[8] as well as Sagnac and Mach-Zehnder interferometers with multimode fiber arms.[7,9] Later we discuss other controllable parameters that allow for selective encoding of portions of input information.

Figure 3 shows the basic setup for all our experiments. The extraordinarily polarized beam from an argon ion laser operating at 488 nm without an etalon is beam expanded and split by a variable beamsplitter (VBS) into two input beams 4 and 2, which are then directed into opposite sides, z = 0 and z =

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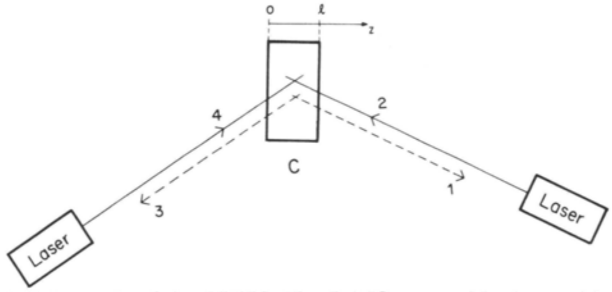

Fig. 1. Schematic of the DPCM: The $BaTiO_3$ crystal is denoted by C. Note that input beams 2 and 4 can be derived from the same laser or from two different sources (as drawn).

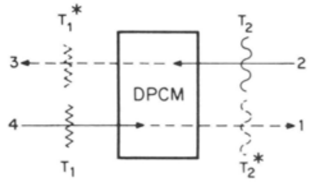

Fig. 2. Schematic of the DPCM acting as a spatial light modulator. Input beams 4 and 2 carry information T_1 and T_2, respectively. Output beam 3, originating from beam 2, loses all the information it carried while propagating in the crystal and is modulated by beam 4 to carry its phase-conjugated information. The same occurs with output beam 1, which is modulated by beam 2.

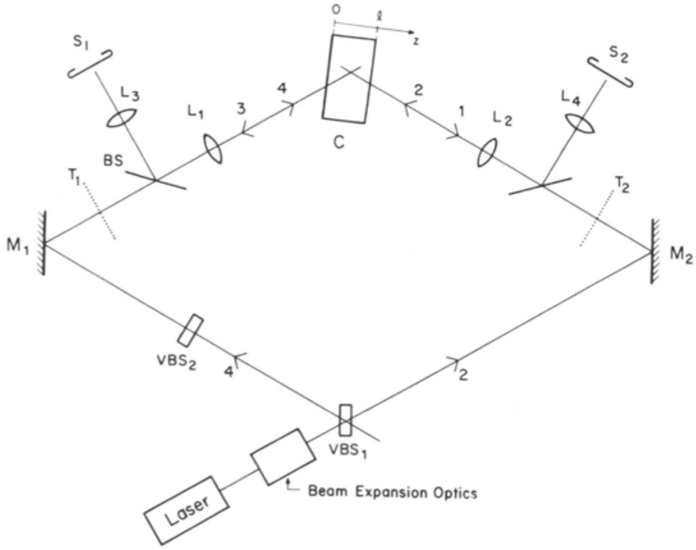

Fig. 3. Schematic of the experimental setup: VBS = variable beamsplitter, BS = beamsplitter, T = transparency, L = lens, C = crystal, S = screen.

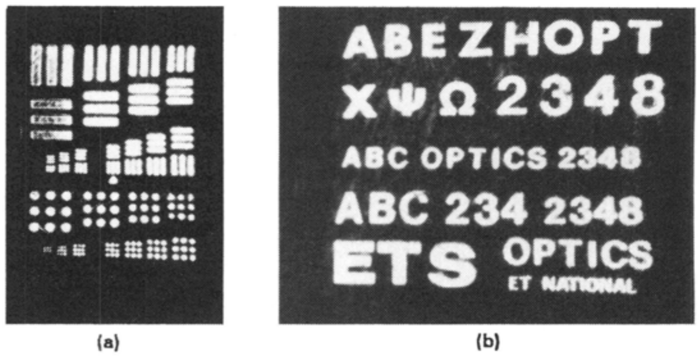

Fig. 4. Output beams 3 and 1 of the DPCM seen simultaneously at (a) S_1 and (b) S_2. The pictures display a resolution of better than 5 lines/mm.

ℓ, of a photorefractive $BaTiO_3$ crystal. The crystal's c axis is parallel to the z axis in the figure. The angle between beams 4 and 2 in the crystal is approximately 173°. In a previously reported experiment,[7] the two beams passed through different transparencies T_1 and T_2 and were loosely focused and guided into the crystal by lenses L_1 and L_2 (both having a focal length of 150 mm), where they overlapped. The two output beams 3 and 1 emerged simultaneously as a result of the 4WM process described earlier, carrying the full pictorial information of the inputs 4 and 2, respectively. These images, seen at screens S_1 and S_2, are shown in Fig. 4.

This two-way information encoding occurs without crosstalk; that is, output 1, although derived from input 4, carries none of that input's information. Similarly, output 3 is derived from input 2 but bears no semblance to that input. We discuss this absence of crosstalk in the DPCM elsewhere.[10]

Another possible filtering implementation with the DPCM would involve the selective erasure of gratings in the mixing plane by an additional beam,[1] which might be polychromatic or have a different wavelength from the interacting beams.

The DPCM can also be described as a bidirectional holographic lens. For example, it can be used to form, in real time, two-way optical information links between 2-D matrix ports (such as single or multimode fiber arrays) located on both sides of the crystal.

3. OPTICAL THRESHOLDING

The DPCM can act as an image amplifier, since the reflectivity of the device can be made higher than unity for large enough $|\gamma\ell|$, where γ is the coupling constant. If the signal is to be amplified uniformly over a wide dynamic range, we need large $|\gamma\ell|$. On the other hand, for low $|\gamma\ell|$, the dynamic range of the device decreases, enabling thresholding operations on gray-leveled images. Other thresholding configurations have been suggested in the past.[11]

A theoretical analysis, summarized below, shows that the DPCM operates over a smaller dynamic range than that of the standard externally pumped phase conjugate mirror (EPPCM) using 4WM, or the 2WM device,[1] and may be more suitable for this kind of processing.

The parameter used to describe the relative intensities of the beams entering the crystal in 4WM configurations is q, defined most generally (for the EPPCM) as[3]

$$q \equiv \frac{I_4(0)}{I_1(0) + I_2(\ell)} , \tag{1}$$

where $I_i(z) = |A_i(z)|^2$ is the intensity of beam i at z. We define dynamic range as that range of q in which the reflectivity of the 4WM device is within 3 dB of maximum. It is interesting to note that for the DPCM, $I_1(0) = 0$, so that it is actually a physical realization of the EPPCM with a pump ratio $r \equiv I_2(\ell)/I_1(0) = \infty$. Figure 6 of Ref. 3 shows that as r approaches this limit, the dynamic range of the EPPCM decreases dramatically.

This is clarified in the following analysis. The intensity transmission T for the DPCM is equal in both directions, i.e., $T = I_3(0)/I_2(\ell) = I_1(\ell)/I_4(0)$, and is related to q [where q for

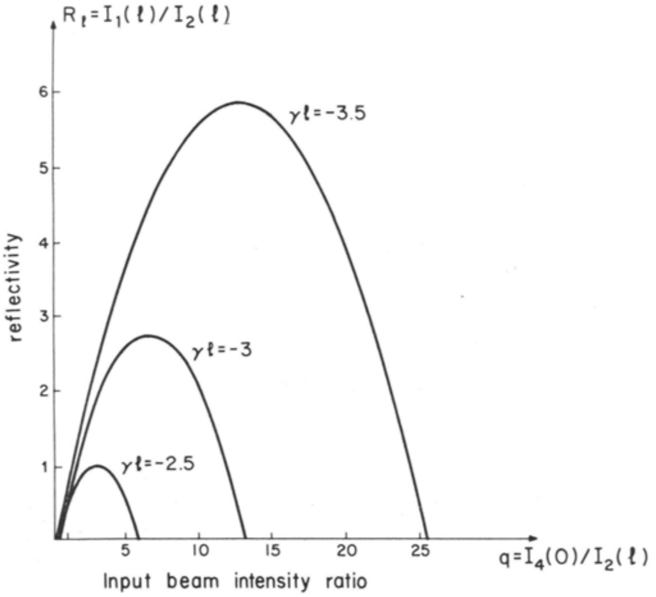

Fig. 5. Plot of phase conjugation reflectivity (on the right side of the crystal) versus the input beam intensity ratio, for several values of $\gamma\ell$.

the DPCM is $I_4(0)/I_2(\ell)$] by

$$T = \frac{a^2(q^{-1/2} + q^{1/2})^2 - (q^{-1/2} - q^{1/2})^2}{4} , \tag{2}$$

where

$$\tanh\left(\frac{-\gamma\ell}{2} a\right) = a \tag{3}$$

and we assume negligible absorption. Equation (2) gives the lowest threshold for $\gamma\ell$; that is, $|\gamma\ell_t| = 2$.

The reflectivities of the DPCM are $R_0 = I_3(0)/I_4(0)$ and $R_\ell = I_1(\ell)/I_2(\ell)$ so that $R_0 = T/q$ and $R_\ell = Tq$. In Fig. 5 R_ℓ versus q is plotted for several values of $\gamma\ell$. We see that, for increasing $|\gamma\ell|$, both the reflectivity and dynamic range increase. For $\gamma\ell = -3$, the dynamic range of q is approximately 9, or less than one order of magnitude. For both the EPPCM and 2WM devices, the dynamic range encompasses at least two orders of magnitude for comparable $\gamma\ell$.[1,3]

In an experiment, the beam expansion optics of Fig. 3 were repositioned just behind the VBS_1 so that only beam 2 was expanded. T_1 was removed and T_2 was a gray-leveled transparency with a dynamic range of more than one order of magnitude. Its hard print is shown in Fig. 6(a). The focal length of both lenses L_1 and L_2 was 10 cm. Lens L_2 was positioned 110 cm from T_2 and 11 cm from the crystal midplane so that it imaged the transparency with a reduction of 10:1 into the crystal, with a beam diameter of 2 mm. Lens L_1 was 16 cm from the crystal midplane. The diameter of beam 4 in the crystal was 2.5 mm. The two variable beamsplitters VBS_1 and VBS_2 were adjusted to select the required q value, which was determined by measuring the intensity of each level in beam 2 and the intensity of beam 4.

Figures 6(b), 6(c), and 6(d) show the fine-tuning capability of the device in performing thresholding. Within the dynamic range of the image, the ability to distinguish between adjacent levels is apparent. The measured cutoff value for q lies between 11 and 15. From the graph of Fig. 5, this implies that $|\gamma\ell|$ for this crystal in the DPCM configuration is about 3. A similar value was measured for the same crystal acting as a 2WM amplifier.

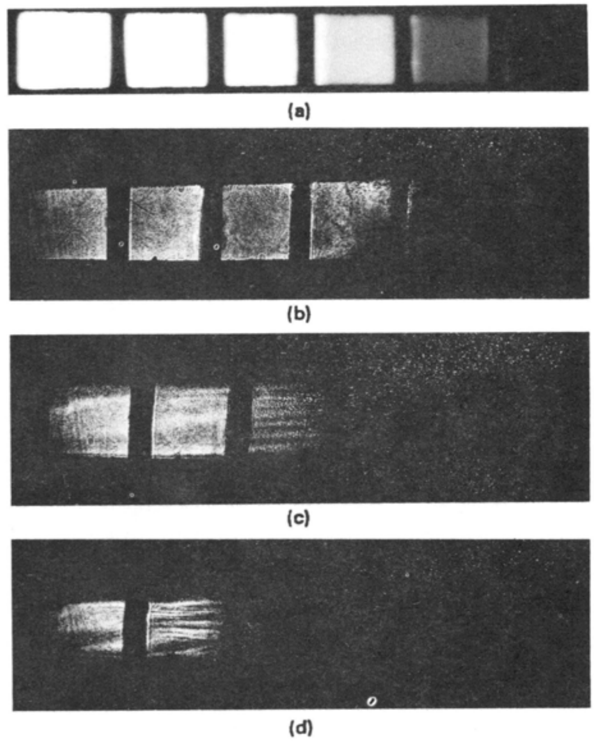

Fig. 6. (a) The gray-leveled transparency used for thresholding experiments. (b) – (d) Thresholding results for different q values.

4. EDGE ENHANCEMENT

Edge enhancement has been demonstrated in the past using an EPPCM as well as with 2WM.[1,4–6] These techniques are based on selective enhancement of the gratings written by the relatively lower intensity components of a signal beam with an appropriate reference beam. In the image plane of a binary signal, this corresponds to the edges of the image. In the Fourier plane, the lower intensity information usually corresponds to the high spatial frequency components of the signal (such as the edges) in the wings of the spectrum distribution. Thus, using the thresholding properties of the DPCM, it is possible to select only the high frequency components of the information and reflect the edge-enhanced image of the signal.

In an experiment we conducted, T_1 of Fig. 3 was removed and T_2 was a resolution chart. The focal length of lenses L_1 and L_2 was 15 cm. First, complete phase conjugation was achieved by loosely focusing beams 2 and 4 into the crystal. Lens L_1 was 13.5 cm from the crystal midplane. The intensity of beam 4 was 2.3 mW with a diameter of 2 mm in the crystal. Lens L_2 was 24.5 cm from the chart and 16.5 cm from the crystal midplane. The intensity of the signal-bearing beam 2 was 4.2 mW with a diameter of 1.5 mm in the crystal. The phase conjugate output of beam 2, observed on screen S_2, is shown in Fig. 7(a). Figure 7(b) is an overhead photograph of the light beams that developed in the crystal during the DPCM's operation. The signal-bearing beam 2 is seen entering the right side of the crystal and beam 4 entering the left

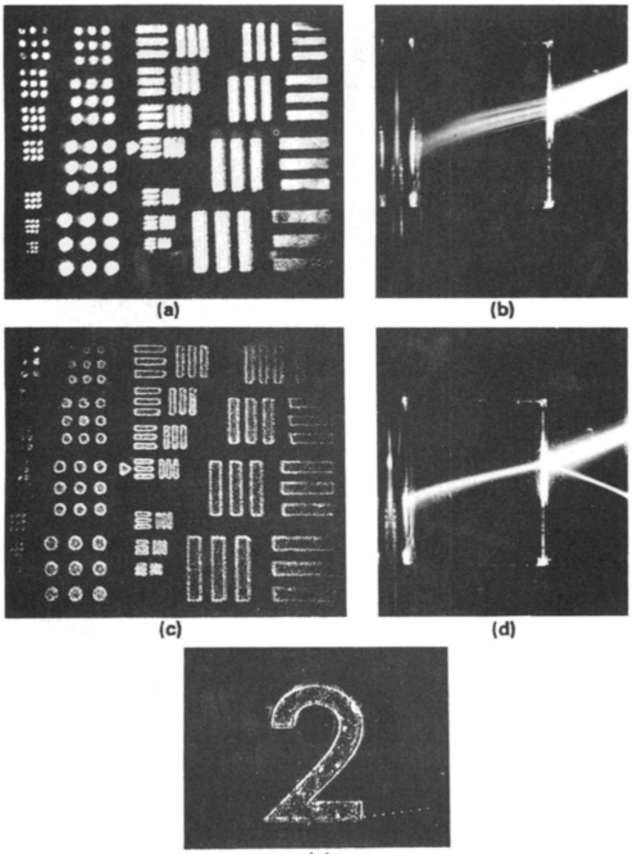

Fig. 7. (a) Phase conjugation of the resolution chart used in the edge enhancement experiment. (b) Overhead photograph of the crystal during full phase conjugation operation. (c) The edge-enhanced signal of Fig. 7(a). (d) Overhead photograph of the crystal during edge enhancing. (e) Edge enhancement of the character 2.

side. The interaction region in the DPCM seems to be relatively large.

To achieve edge enhancement, L_2 was repositioned 15 cm from the crystal so that beam 2 in the crystal was the Fourier transform of the signal (resolution chart or the character 2). Lens L_1 was also shifted to 12.5 cm from the crystal so that beam 4 was much wider than beam 2 and completely overlapped it in the crystal. This was done to ensure that gratings would develop in the side lobes of beam 2, where the high spatial frequency information is located. In addition, both VBSs were rotated to increase $I_2(0)$ and decrease $I_4(\ell)$ until optimum edge enhancement was observed on screen S_2. The optimum intensity of beam 2 was 5.7 mW with a diameter of 0.3 mm in the crystal, and that of beam 4 was 0.7 mW with a diameter of 3 mm. The edge-enhanced signals are shown in Figs. 7(c) and 7(e). An overhead photograph of the DPCM during this operation is shown in Fig. 7(d). Note the intensity doublets of the enhanced edges, which are similar to the results described in Ref. 5.

The mechanism behind this processing is clear: the intensity of weak beam 4 optimized q for the edge information; for the stronger low frequency information, q deviated from the narrow dynamic range of the DPCM so that efficient gratings did not form.

As stated earlier, input beams 4 and 2 were not mutually coherent and may even be derived from different lasers, as opposed to other wave-mixing devices, which require coherency of the input beams.

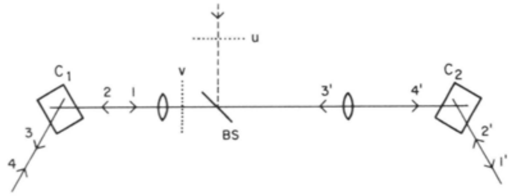

Fig. 8. Schematic of the 2FDPCM (symbols as in Fig. 3). Here, u and v are complex spatial modulators in the beam paths.

5. ITERATIVE IMAGE PROCESSING WITH TWO FACING DPCMs

We have demonstrated a new photorefractive oscillator based on two facing DPCMs (2FDPCMs), as shown in Fig. 8.[7] As for the single DPCM, the inputs 4 and 2 to crystal 1, or 4′ and 2′ to crystal 2, may be spatially complex, need not be mutually coherent, and may be derived from different lasers. A photorefractive oscillation consisting of counterpropagating phase conjugate beams builds up between the two crystals. This oscillation can support spatial information, such as that of slide v in the cavity, even with the presence of a multimode fiber in the beam path. Beams 4 and 2′ are also simultaneously phase conjugated by the two DPCMs.

This resonator may be useful as an optical means of realizing iterative image processing algorithms such as inverse filters and phase retrieval. The implementation of a Wiener filter with two facing PCMs has been suggested before.[12,13] Note that optical information can be addressed either by placing a modulation medium in the cavity itself (such as the slide v in the figure) or through external injection via a beamsplitter situated inside the cavity. Our recent work on the lack of crosstalk in the DPCM[10] indicates that information cannot be injected into the cavity via beams 4 and 2′.

As an example of inverse filtering, consider the schematic shown in Fig. 8. Here, v is a complex modulator in the cavity, and u is externally applied via the beamsplitter. A simple calculation shows that the signal s that builds up iteratively in the cavity takes the form

$$s = \frac{ruv^*}{\dfrac{1}{\rho_1\rho_2 t^*} - t|v|^2} \tag{4}$$

to the left of modulator v, where ρ_1 and ρ_2 are the complex amplitude reflectivities of the two DPCMs (looking into the cavity) and can be controlled with q and $\gamma\ell$ to be higher or lower than unity, r is the beamsplitter reflectivity, and t is the combined transmissivity of the cavity, including the beamsplitter and other optics.

For $\rho_1\rho_2|t|^2 >> 1/|v|^2$,

$$s \propto \frac{-r}{t}\,\frac{u}{v}\,. \tag{5}$$

In this fashion, one can achieve image division (for u and v image distributions) or inverse filtering (if u and v are modulations in the frequency plane). This requires reflectivity amplification from the DPCMs and can be achieved for sufficiently high $|\gamma\ell|$, as shown in Fig. 5. Note that if v has a large dynamic range of gray levels, the requirements on ρ_1 and ρ_2 are more severe.

Recently, some groups have discussed the use of PCM resonators to implement an associative memory.[14–16] Partial results have been reported using photorefractive $BaTiO_3$. We suggest the use of the 2FDPCM to implement such a device since it has the two essential features for this kind of iterative processing, namely, thresholding and gain. The requirements of thresholding on one side of the resonator and gain on the other side can be realized with two different crystals with appropriate values of $\gamma\ell$, as shown in Fig. 5.

The ability to phase conjugate high spatial frequencies, with possible amplification, may also allow, for example, the implementation of Gerchberg's super-resolution algorithm.[17] For this application, one of the DPCMs in Fig. 8 (with some modification in the positions of the elements in the cavity) would operate in the high-pass PCM mode and the other as a regular PCM. The input u is a truncated spectrum of a diffraction-limited (or blurred) finite object, and v is a filter in the spatial plane that constrains the oscillation to the known finite extent of the object. These elements should be sufficient to iteratively extrapolate in the cavity the lost high spatial frequencies of the input object.[17] A passive optical processor using regular mirrors has been proposed to implement this algorithm.[18] The processor described here has the obvious advantages of phase conjugation and gain.

6. CONCLUSIONS

We have presented the DPCM as a unique spatial light modulator, in which two optical image bearing beams modulate each other, enabling controllable filtering of information. Applications in image processing, interferometry, beam coupling, and laser locking have already been discussed elsewhere.[7–9]

Here, we demonstrate optical processing operations such as thresholding and edge enhancement and discuss possible implementation of iterative image processing algorithms. The phase conjugation reflectivity of the DPCM has a relatively narrow dynamic range (for small $|\gamma\ell|$), enabling selective reflection of portions of the input information, such as high-pass filtering, edge enhancement, and thresholding operations.

The 2FDPCM has been shown to be a sophisticated resonator, composed of two phase conjugation mirrors, each of which can operate in amplifying or thresholding mode. Further efforts to demonstrate the implementation of image processing algorithms with this resonator are planned.

7. ACKNOWLEDGMENT

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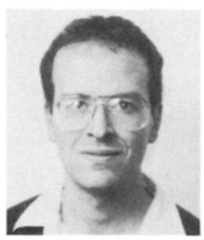
8. REFERENCES

1. Y. Fainman, E. Klancnik, and S. H. Lee, "Optimal coherent image amplification by two-wave coupling in photorefractive $BaTiO_3$," Opt. Eng. 25(2), 228–234 (1986); Y. Fainman, C. C. Guest, and S. H. Lee, "Optical digital logic operations by two-beam coupling in photorefractive materials," Appl. Opt. 25, 1598 (1986).
2. T. R. O'Meara, D. M. Pepper, and J. O. White, "Applications of nonlinear optical phase conjugation," in *Optical Phase Conjugation*, R. Fischer, ed., pp. 537–589, Academic Press, New York (1983).
3. M. Cronin-Golomb, B. Fischer, J. O. White, and A. Yariv, "Theory and applications of four-wave mixing in photorefractive media," IEEE J. Quantum Electron. QE-20, 12 (1984) and references cited therein.
4. J. P. Huignard and J. P. Herriau, "Real-time coherent object edge reconstruction with $Bi_{12}SiO_{20}$ crystals," Appl. Opt. 17, 2671 (1978).
5. J. Feinberg, "Real time edge enhancement using the photorefractive effect," Opt. Lett. 5, 330 (1980).
6. E. Ochoa, J. W. Goodman, and L. Hesselink, "Real time enhancement of defects in a periodic mask using photorefractive $Bi_{12}SiO_{20}$," Opt. Lett. 10, 430 (1985).
7. S. Weiss, S. Sternklar, and B. Fischer, "The double phase conjugate mirror: analysis, demonstration and applications," Opt. Lett. 12, 114(1987).
8. S. Sternklar, S. Weiss, M. Segev, and B. Fischer, "Beam coupling and locking of lasers by using photorefractive four-wave mixing," Opt. Lett. 11, 528 (1986).
9. S. Sternklar, S. Weiss, M. Segev, and B. Fischer, "Mach Zehnder interferometer with multimode fibers using the double phase conjugate mirror," Appl. Opt. 25, 4518(1986).
10. B. Fischer, S. Weiss, and S. Sternklar, "Spatial light modulation and filtering effects in photorefractive wave mixing," Appl. Phys. Lett. (March 1987).
11. M. B. Klein, G. J. Dunning, G. C. Valley, R. C. Lind, and T. R. O'Meara, "Imaging threshold detector using a phase conjugate resonator in $BaTiO_3$," Opt. Lett. 11, 575 (1986).
12. O. Ikeda, T. Sato, and H. Kojima, "Analysis of a high-resolution and large-dynamic range spatial filter using a pair of facing phase conjugators with gain," J. Opt. Soc. Am. A 2, 1983 (1985).
13. O. Ikeda, T. Sato, and H. Kojima, "Construction of a Wiener filter using a phase-conjugate filter," J. Opt. Soc. Am. A 3, 645 (1986).
14. D. Z. Anderson, "Coherent optical eigenstate memory," Opt. Lett. 11, 56 (1986).
15. B. H. Soffer, G. J. Dunning, Y. Owechko, and E. Marom, "Associative holographic memory with feedback using phase-conjugate mirrors," Opt. Lett. 11, 118 (1986).
16. A. Yariv and S. K. Kwong, "Associative memories based on message-bearing optical modes in phase-conjugate resonators," Opt. Lett. 11, 186 (1986).
17. R. W. Gerchberg, "Super-resolution through error energy reduction," Opt. Acta 21, 709 (1974).
18. R. J. Marks II, "Coherent optical extrapolation of 2-D bandlimited signals: processor theory," Appl. Opt. 19, 1670 (1980).



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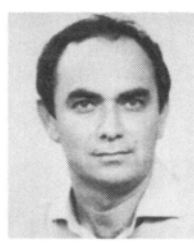

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