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Photorefractive optical recycling for contrast enhancement

John E. Heebner *, Robert W. Boyd

Institute of Optics, University of Rochester, Rochester, NY 14627, USA

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Abstract

Optical processing via high-pass filtering is a well-established means of enhancing image contrast. However, this procedure is energetically inefficient, because the power associated with the low-spatial-frequency components of the image is ordinarily discarded. We demonstrate a means of performing contrast enhancement in an energy efficient manner, by recycling the optical power ordinarily discarded using photorefractive two-beam coupling in barium titanate. © 2000 Elsevier Science B.V. All rights reserved.

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The techniques of image processing for contrast enhancement derived from linear systems theory are well established, but nevertheless limited. Signal contrast may be improved by filtering out the constant object background, which corresponds to low spatial frequencies. For an object of low contrast, this rejected background component comprises most of the optical power, and its removal, while enhancing contrast, results in a weak image. It would be desirable to perform contrast enhancement optically, without loss of power. We demonstrate a system in which the ordinarily wasted background light is recycled for use as a pump source used to amplify the filtered signal using photorefractive two-beam coupling in barium titanate. A substantial increase in throughput efficiency may be achieved in this manner. In some respect, our technique is similar to the techniques of ‘beam-cleanup’ [1–4] and efficient unpolarized-to-polarized light conversion [5] in which light ordinarily rejected is collected and used as a pump to increase the power throughput of ‘beam-cleanup’ and polarizing systems respectively.

A standard optical processor is constructed from two lenses separated by the sum of their focal lengths (Fig. 1). Such a system takes an input object at the front focal plane of the first lens and forms an inverted image at the back focal plane of the second lens. If the optical field leaving the object is coherent, the two-dimensional Fourier transform of the object is formed at the back focal plane of the first lens providing a mapping of object spatial frequency to position. Modifications performed on the field at this plane alter the spatial-frequency transfer characteristics of the system, which in turn can provide

* Corresponding author. Tel.: +1-716-275-5030; fax: +1-716-244-4936, e-mail: heebner@optics.rochester.edu

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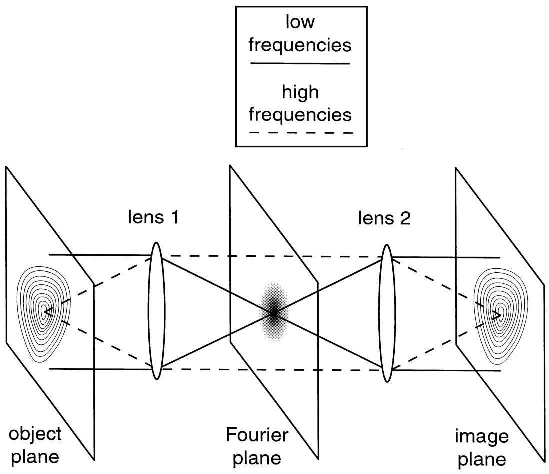

Fig. 1. A standard optical processor. This configuration may be employed as a high-pass optical filter by introducing a small circular light stop on axis at the Fourier plane. The stop removes the low-spatial-frequency components in the image.

global changes to the properties of the final image. In particular, a high-pass filter is achieved by placing a circular stop (the complement of a pinhole) in the Fourier plane on the optical axis. Such a system can remove the background component of an object field and thus yield an image with improved contrast. A well known application for an optical high-pass filter is to provide a means of visualizing phase objects such as fingerprints. The field of a phase object of unit amplitude can be expanded in a Taylor's series as:

$$e^{i\phi(x,y)} = 1 + i\phi(x,y) + \tfrac{1}{2}[i\phi(x,y)]^2 + \dots \quad (1)$$

Removing the zero-order component and retaining only the first-order term is a good approximation for the amplitude of a filtered, weak phase object at its image plane. The intensity at such an image plane is thus proportional to the square modulus of the phase function:

$$I_{\text{filtered}} \propto \left| e^{i\phi(x,y)} - 1 \right|^2 \approx |\phi(x,y)|^2. \quad (2)$$

In practice, this technique is known as the central dark ground method of observation [6]. In our experiments we make use of this technique and employ a coherently illuminated fingerprint as a test phase object.

Our technique for optical recycling entails using the power in the removed zero-order component as a pump to amplify the first-order (signal) using photorefractive beam coupling. The photorefractive effect [7,8] occurs in certain noncentrosymmetric nonlinear materials in which the redistribution of optically excited charge carriers leads to a modification of the refractive index. Two optical waves propagating in a photorefractive material form a modulated intensity pattern which in turn forms a modulated refractive index distribution or grating. Because the grating is formed by interference of the two waves, it provides exact phase matching for the two waves, and each diffracts from the grating into the other's direction of propagation. For photorefractive materials such as barium titanate, the index grating is spatially shifted with respect to the intensity pattern by a phase of $\pm\pi/2$ radians, the sign depending upon the crystal orientation. This phase shift allows one diffracted beam to interfere constructively with the zero-order component of the other, thus providing gain, while the other pair of diffracted and zero-order beams interferes destructively, attenuating the other beam. The beam-coupling dynamics are governed by the following pair of coupled-wave equations [9,10]:

$$\frac{d}{dz} I_s = \Gamma \frac{I_s I_p}{I_s + I_p}\,; \quad \frac{d}{dz} I_p = -\Gamma \frac{I_s I_p}{I_s + I_p}\,. \quad (3)$$

Here, I_s and I_p are the signal and pump intensities and Γ is the photorefractive gain coefficient. Energy transfer is unidirectional, independent of the phase difference between the two input beams, and can occur at milliwatt power levels. Photorefractive beam coupling is thus an attractive choice for the monotonic amplification of a signal-bearing beam at the expense of another mutually coherent, though not necessarily spatially clean, pump beam.

To demonstrate our technique, we employ the setup shown in Fig. 2. A fingerprint on a glass slide is illuminated with a collimated helium-neon laser beam at 633 nm. A lens placed one focal length away ($f = 10$ cm) forms the two-dimensional Fourier transform of the object field at its back focal plane. The background comes to a focus on the optical axis while the signal is distributed off the axis. Here we place our high-pass filter which consists of a silvered

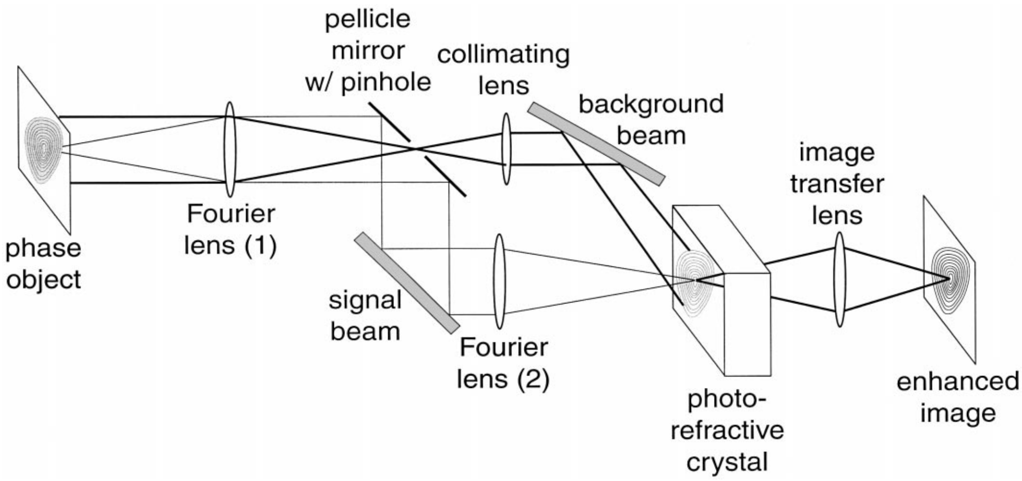

Fig. 2. Setup used to amplify the contrast-enhanced signal beam by photorefractive optical recycling. The rejected low-spatial-frequency background beam is used as a pump to amplify the signal beam by photorefractive two-beam coupling.

pellicle mirror containing a hole in the center to separate the background from the signal. The signal reflects from the mirror, while the background passes through the hole. One lens re-images the signal, while another collimates the background. The background now takes the form of a clean beam which is redirected by a mirror to overlap with the signal field in a crystal of barium titanate which is properly oriented to allow power transfer from the background to the signal. The signal beam experiences gain at the expense of the background beam via two-beam coupling throughout the overlapping region in the crystal. A final lens is used to re-image the amplified signal field onto a beam profiling CCD camera. Because the tightest confinement and thus highest intensity of the signal beam occurs at the intermediate image plane, we have chosen to locate the photorefractive crystal in this plane. However, our photorefractive recycling scheme would work equally well if the crystal were placed at some other plane along the direction of propagation.

In Fig. 3 we present a qualitative comparison of images of the fingerprint captured electronically on a CCD camera for 4 cases. Fig. 3(a) is the raw, unprocessed image of the fingerprint passed through the optical processor without any filter elements. In Fig. 3(b) the object passes through a high-pass filter to enhance contrast, but is rendered extremely weak in the process. We then proceeded to amplify the contrast-enhanced image in two ways. First we captured the data and multiplied the results by a factor of 81 (for comparison with the next case). As can be seen in Fig. 3(c), the image fidelity is corrupted by noise because the image power is close to the background and/or noise level of the CCD camera. Secondly, we allowed the split-off low-frequency beam to pre-amplify the signal by means of our optical recycling method. A gain of 81 was achieved by use of this technique. Fig. 3(d) shows that images obtained in this manner preserve fidelity and brightness, while maintaining enhanced image contrast. Here, some vignetting has occurred because of the falloff in gain as a result of the decreased intensity on the wings of the pump beam transverse intensity distribution.

The data taken from the fingerprint images were then analyzed to quantify image contrast. The unprocessed image of the initial object possessed an optical power of 1.1 mW but with a poor contrast of about 0.1%. High-pass filtering alone provided an enhanced image contrast of approximately 70% although with a low power of 1.4 μW. High-pass filtering followed by photorefractive amplification maintained the high contrast of 70% while amplifying (81X) the power to 110 μW. The results of our theoretical model (described in detail below) show that the efficiency was limited primarily by the short length of the barium titanate crystal used in our

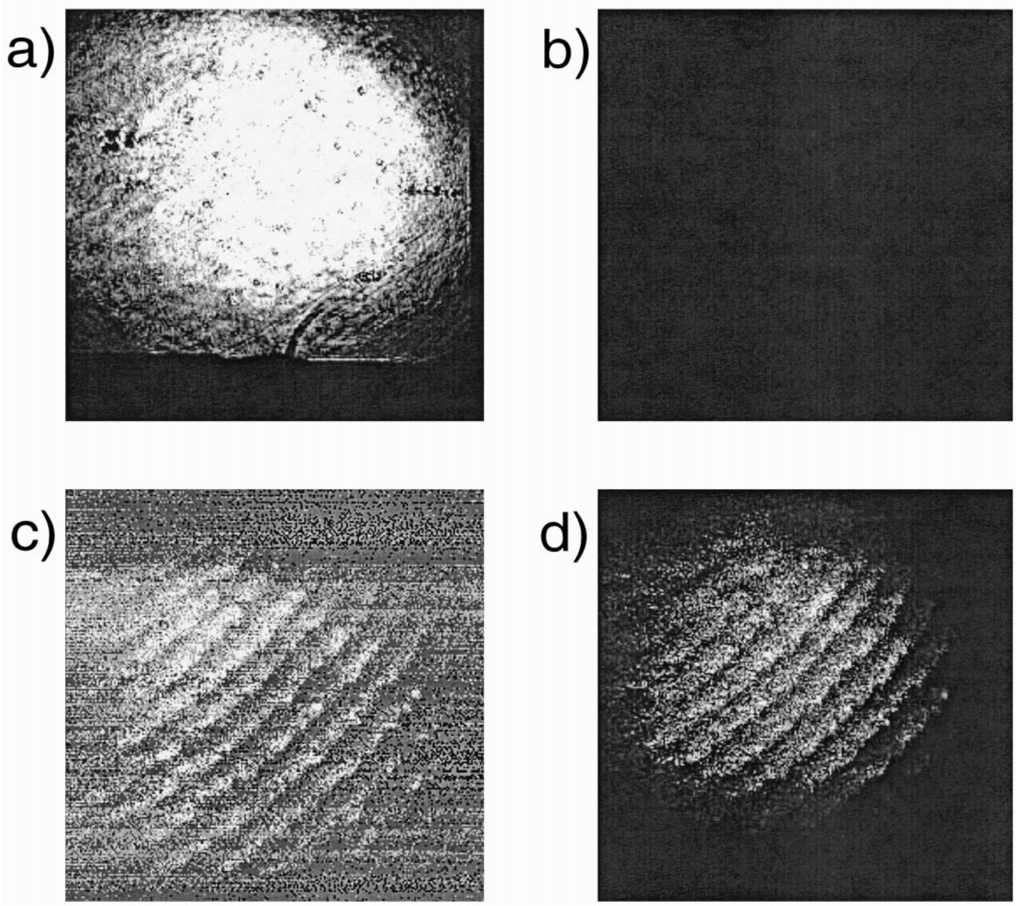

Fig. 3. Images of a fingerprint taken under 4 conditions: (a) raw fingerprint image, (b) contrast enhanced, but severely weakened image, (c) contrast enhanced, digitally amplified image (d) contrast enhanced, optically amplified image using recycled light.

experiment. Through use of a crystal 10 mm long, essentially complete transfer of power to the signal beam is predicted. In our laboratory demonstration, losses due to absorption were approximately 30%, and losses due to beam-fanning [11] were negligible.

Objects possessing extremely weak contrast require longer interaction lengths or stronger coupling strengths (Γ) for power transfer to proceed to saturation. The solution to the photorefractive coupled wave Eqs. (3) which includes the effects of pump depletion is given by:

$$R(z) = \frac{R(0)\mathrm{e}^{\Gamma z}}{R(0)\left[\mathrm{e}^{\Gamma z} - 1\right] + 1}, \tag{4}$$

where $R(z)$ represents the fraction of the total power contained in the signal as a function of interaction distance. Fig. 4 shows theoretical plots of the throughput efficiency versus interaction length for a typical coupling strength of 1.0 mm^{-1}. The set of

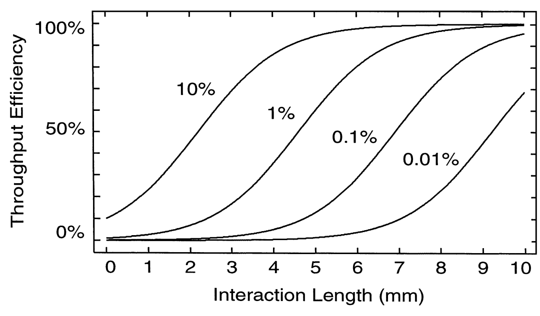

Fig. 4. Theoretical throughput efficiency versus interaction length for various initial object contrasts.

curves represents different cases in which the initial object contrast is varied. As can be seen, to obtain a given recycling efficiency, objects of lower contrast require a longer interaction lengths. For a desirable near-unit throughput efficiency, the required interaction length is approximately given by

$$L \approx \frac{1}{\Gamma}\ln\left(\frac{1}{2C}\right), \qquad (5)$$

where C is the initial object contrast which, for weak contrast is nearly equal to half of the initial fraction of signal power $R(0)$. Our experiments correspond to the 0.1% contrast curve where throughput efficiency is limited to approximately 10% for a crystal length of 5 mm. Note that a 10 mm barium titanate crystal of comparable interaction strength would be capable of delivering near unit throughput efficiency for initial object contrasts similar to those used in this experiment.

Photorefractive beam coupling can inherently act as an image amplifier [12] and/or a high-pass filter, for both spatial frequencies and temporal frequencies. Optical processing schemes involving edge enhancement [13], contrast enhancement [14], phase visualization [15] and novelty filtering [16,17] have been demonstrated using the spatial and temporal frequency dependent properties of photorefractive beam coupling. Our scheme leaves the optical processing to the more robust, traditional methods and supplements them by making use of the photorefractive process as an amplifier. In theory, the traditional methods of optical processing by separation of spatial frequency components may be made 100% efficient through use of our scheme.

The principle of phase contrast microscopy demonstrated by Zernike [18] is one of the standard techniques used in the biological sciences for the imaging of transparent microorganisms. While similar to ordinarily high-pass filtering as described in this letter, it differs in that a fraction of the low-frequency power is retained, phase shifted by one quadrature, and made to interfere with the signal component. The extra advantage offered by this technique is the same that is gained by heterodyne mixing, interferometry, or holography: the signal phase may be mapped directly into intensity. Nevertheless, typically only a small fraction of the low-frequency component is retained as a reference while a substantial amount of power is discarded. We envision that the techniques of phase contrast microscopy may be supplemented by our recycling mechanism in much the same way as demonstrated in this letter so as to substantially increase the throughput efficiency of conventional phase contrast microscopes.

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