Edge enhancement by using two-wave mixing and its application to pattern recognition

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Coupling theory is employed to analyze coupling gain and a new optical system is proposed for image edge enhancement, in which the ordinarily discarded background light is recycled as a pump source to amplify the signal light. We demonstrate the principle of optical correlation and compare the discrimination capability of two kinds of correlators by computer simulation. The results show that edge enhancement preprocessing can improve discrimination capability effectively.

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Real-time optical image processing such as edge enhancement has been widely investigated in recent years because of its unique property[1]. However, it mainly focuses on filtering out low spatial frequency component. For an image with less high spatial frequency component, this rejected component comprises most of the optical power, and its removal, while enhancing image edge, results in a weak image and loss of useful information. Here we present a new optical system for image edge enhancement by using two-wave coupling.

Of all the techniques for optical image processing, perhaps two-wave mixing is most versatile. According to the Kukhtarve-Vinetskii model, without considering the absorption of crystal, the energy coupling equations can be written as[2]

$$\frac{\mathrm{d}}{\mathrm{d}z}I_{\mathrm{p}} = -\Gamma\frac{I_{\mathrm{p}}I_{\mathrm{s}}}{I_{\mathrm{p}}+I_{\mathrm{s}}},\quad \frac{\mathrm{d}}{\mathrm{d}z}I_{\mathrm{s}} = \Gamma\frac{I_{\mathrm{p}}I_{\mathrm{s}}}{I_{\mathrm{p}}+I_{\mathrm{s}}}, \tag{1}$$

where Γ is the coupling coefficient. Equation (1) shows that the two beams can be either amplified or attenuated depending on the sign of the coupling coefficient. When Γ is negative, the energy will flow from I_{s} to I_{p}, and *vice versa.*

Early study[2] shows that the direction of energy transfer between the two beams depends on the crystal orientation and sign of the photo-induced charge carriers, the magnitude of the coupling depends on material parameters such as trap density and effective electro-optic coefficient. For $\mathrm{BaTiO_3}$ crystal, its largest electro-optic coefficient is γ_{42}, generally the light-induced carriers are holes and the energy transfer is toward $+c$ direction. Therefore, if we properly adjust the crystal orientation, the energy may flow from pump beam to signal beam.

In order to depict the direction and magnitude of energy transfer, we redefine the gain g experienced by the signal beam as $g = \ln[I_{\mathrm{s}}(L)/I_{\mathrm{s}}(0)]$, which is different from the previous definition[3]. Under the above condition, we deduce the gain from the coupled wave equations, which is given by

$$g = \ln\{(1+r)\exp(\Gamma L)/[r+\exp(\Gamma L)]\}, \tag{2}$$

where $r = I_{\mathrm{p}}(0)/I_{\mathrm{s}}(0)$ is the intensity ratio between input bump beam and signal beam, L is the effective interaction length. Figure 1 shows the gain g as a function of r for fixed $\Gamma L = 10$. We can see from the curve that the larger the beam intensity ratio r is, the larger the gain g is. For fixed pump beam intensity, the smaller the signal beam intensity is, the larger the gain is.

The new optical system proposed is shown in Fig. 2. In some respects, our technique is similar to the techniques of optical recycling for contrast enhancement[4]. In it, a Fourier lens, which is placed one focal length away from the object, forms the two-dimensional (2D) Fourier transform of the object field at its back focal plane. According to Fourier transform, the background beam with low spatial frequency will focus on the optical axis while the image edge with high spatial frequency will be distributed off the axis. By inserting a totally reflective mirror containing a pin-hole in the center properly at the back focal

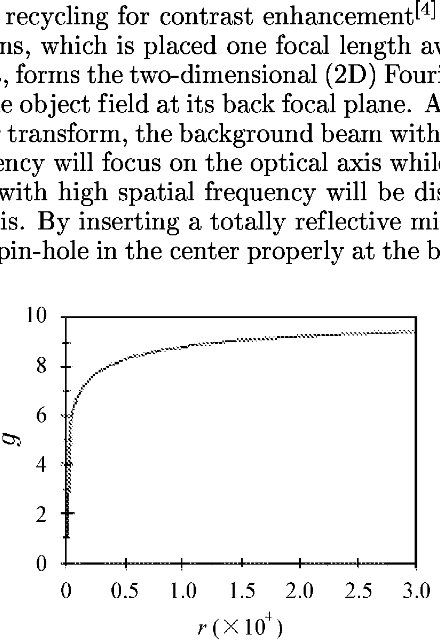


Fig. 1. The gain g versus r.

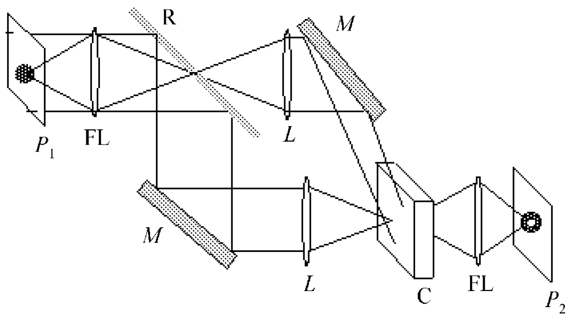


Fig. 2. Experimental setup. L: lens; P_1: input plane; P_2: output plane; FL: Fourier lens; R: totally reflective mirror with a pin-hole; M: mirror; C: crystal.

plane of Fourier lens, the background beam will be separated from signal beam. As a result, the signal beam is reflected from the mirror, while the background beam passes through the pin-hole. By using collimating lens and totally reflective mirrors, both the background beam and the signal beam are incident on crystal properly oriented for the purpose of allowing power to transfer from the background beam to the signal beam.

A joint transform correlator (JTC) used for optical pattern recognition has been paid more attention by researchers[5]. But the correlation discrimination capability is not satisfactory. We will demonstrate the discrimination capability can be improved greatly by using edge enhancement preprocessing.

In the JTC, reference image $r(x-a,y)$ and target image $t(x+a,y)$ are illuminated by a collimated coherent beam. The optical amplitude in the input plane is written as

$$f(x,y) = r(x-a,y) + t(x+a,y). \tag{3}$$

The Fourier transform lens performs the Fourier transform of the input image. After being transformed by square-law converter, the joint transform power spectrum is given as

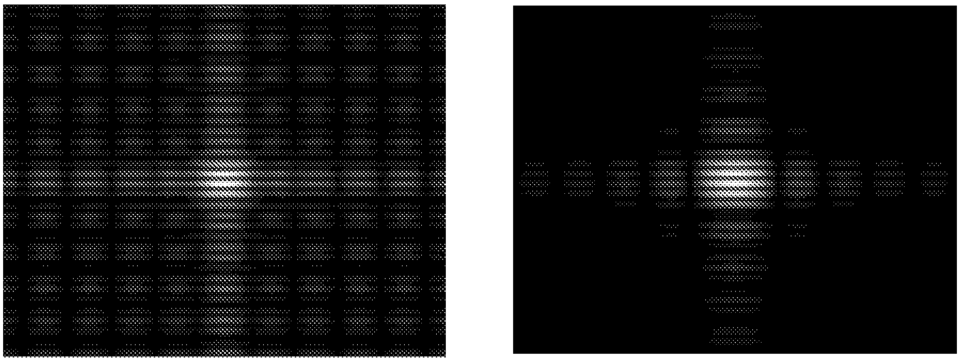
$$\begin{aligned} I(u,v) = |F(u,v)|^2 &= R^2(u,v) + T^2(u,v) + \\ &+R(u,v)T^*(u,v)\exp(-j4\pi ua) \\ &+R^*(u,v)T(u,v)\exp(j4\pi ua), \end{aligned} \tag{4}$$

where "*" represents complex conjugate. Using another Fourier lens, the Fourier inverse transform of the joint transform power spectrum will be obtained as

$$\begin{aligned} f_1(x,y) &= r(x,y) \otimes r(x,y) + t(x,y) \otimes t(x,y) \\ &+r(x-2a,y) \otimes t(x-2a,y) \\ &+t(x+2a,y) \otimes t(x+2a,y), \end{aligned} \tag{5}$$

where the symbol $\otimes$ represents the correlation operation. The first two terms are the autocorrelation and the last two terms are the cross correlation. The above equation shows that the cross correlation terms between the reference image and the target reference are at $(\pm 2a, 0)$ in the output plane. If the reference image is identical to the target image, brighter correlation peaks appear at $(\pm 2a, 0)$, otherwise darker correlation peaks will be obtained.

In the following, we use a pair of square patterns as target image and reference image to demonstrate that edge enhancement preprocessing on input images can improve the discrimination capability of optical correlator. Figure 3 shows the joint transform power spectrum of them. As shown from the figure, the joint transform power spectrum with edge enhancement contains higher frequency information than that without edge enhancement. Figures 4(a) and 5(a) are 3D correlation distribution with and without edge enhancement, respectively. While Figs. 4(b) and 5(b) are the normalized intensity with and without edge enhancement along the horizontal direction, respectively. It is shown from the figures that, after edge enhancement preprocessing on the target and reference images, 1) both auto-correlation and cross-correlation have much sharper peaks compared with



(a) (b)

Fig. 3. Joint transform power spectra. (a) With edge enhancement; (b) without edge enhancement.

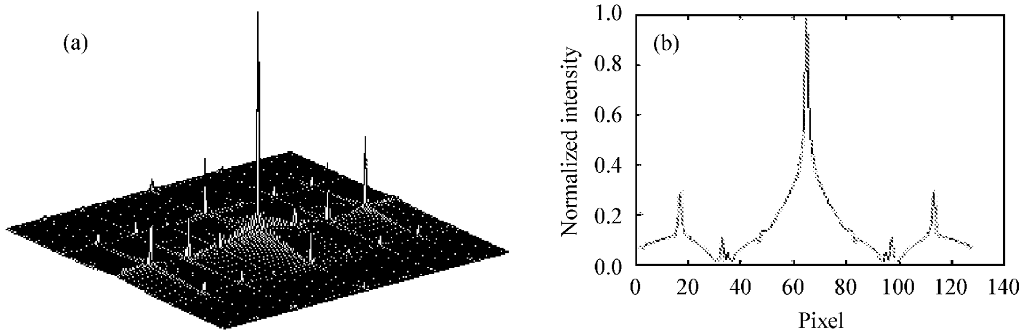


Fig. 4. Joint transform correlation result (with edge enhancement). (a) 3D correlation distribution; (b) normalized intensity curve along the horizontal direction.

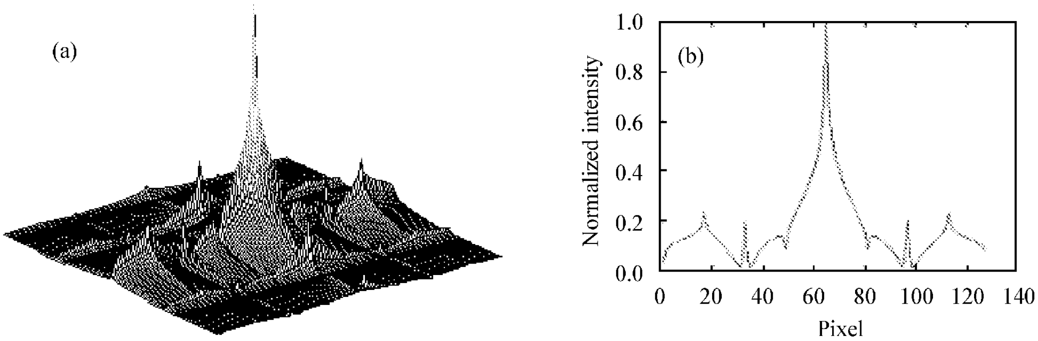


Fig. 5. Joint transform correlation result (without edge enhancement). (a) 3D correlation distribution; (b) normalized intensity curve along the horizontal direction.

that without edge enhancement; 2) discrimination capability[6] R defined as the ratio between cross-correlation peak and auto-correlation takes a value of 0.294 by edge enhancement preprocessing and 0.232 with no edge enhancement.

In summary, we redefine the gain and deduce its expression from the coupled wave equations. A new optical system for image edge enhancement is put forward which is especially effective for weak signal, and we demonstrate theoretically that it can perform edge enhancement. By comparison, we find that optical correlation discrimination capability can be improved greatly by using this optical edge enhancement preprocessing.

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References

1. Z. Q. Wang, B. L. Liang, H. L. Liu, J. H. Guan, and G. G. Mu, Proc. SPIE **4110,** 277 (2000).
2. X. D. Mu, X. G. Xu, J. Chen, Z. S. Shao, and M. H. Jiang, Opt. Commun. **141,** 189 (1997).
3. J. A. Khoury, G. Hussain, and R. W. Eason, Opt. Commun. **70,** 272 (1989).
4. J. E. heebner and R. W. Boyd, Opt. Commun. **182,** 243 (2000).
5. J. L. Zhao, Q. T. Xu, W. M. Zhou, D. S. Yang, S. Kapphan, and R. Pankrath, Opt. Commun. **212,** 287 (2002).
6. M. S. Alam, O. Perez, and M. A. Karim, Appl. Opt. **32,** 3102 (1993).