TECHNICAL NOTE

Shift-invariant photorefractive joint-transform correlator using Fe:LiNbO$_3$ crystal plates

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We report the results of our experimental investigation on a shift-invariant photorefractive image correlator that uses a thin crystal plate of Fe:LiNbO$_3$, which operates in the Raman–Nath regime of diffraction.

Optical image correlators can play an essential role in applications such as machine vision, target detection, and pattern recognition. They have the advantages of processing a large amount of information in a parallel fashion. The joint-transform correlator is one of the most widely studied architectures that perform optical image correlation.[1,2] It is especially suitable for real-time applications when used in conjunction with photorefractive crystals. Over the past few years, a variety of real-time optical image correlators have been demonstrated by using either a spatial light modulator or a photorefractive crystal in the Fourier domain.[3–9] Although the technology of spatial light modulators has advanced rapidly, the devices still have poor resolutions compared with photorefractive crystals. Photorefractive crystals have the capability of real-time operation and an extremely high sensitivity for certain materials such as sillenites and compound semiconductors. On the other hand, owing to the nature of Bragg diffraction from the volume hologram, the photorefractive-crystal-based optical correlators have a narrow field of view, which is responsible for the lack of shift invariance. In this Note, we present experimental studies of a joint-transform correlator that uses a thin photorefractive crystal plate and investigate the shift-invariant properties of the correlator. The results show that, by using the thin photorefractive crystal in the Fourier domain, the correlators have the combined advantages of both high resolution and much-improved shift invariance.

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It is well known from the correlation theorem that the correlation of two images can be obtained through the retransformation of the product of the Fourier transforms. Referring to the general architecture of the photorefractive joint-transform correlator as shown in Fig. 1, we consider coherent collimated beams that are spatially modulated by transparencies or spatial light modulators. The object $[A_1(x, y)]$ and the reference $[A_2(x, y)]$ images are Fourier transformed by the lenses and form an interference pattern, i.e., a hologram, in the photorefractive crystal. The modulation depth of the hologram is proportional to the product of the two Fourier transforms, i.e., $F^*[A_1(x, y)]F[A_2(x, y)]$. The hologram is read out by a collimated beam A_3, usually mutually incoherent with A_1 and A_2, that is counterpropagating with respect to the center of the reference beam. Since the hologram is written by two image-bearing beams and read out by a plane wave, it belongs to the joint-transform correlator even though two lenses are used. The diffracted beam from the hologram is picked up through a beam splitter and retransformed through a lens displaying the correlation signal, i.e., $A_4(x, y) \sim F^{-1}\{F^*[A_1(x, y)]F[A_2(x, y)]A_3\}$ on a detection device such as a CCD camera. For practical purposes the object and the reference images always contain many pixels of spatial information. The hologram thus consists of many grating components. Since these gratings are all different in their grating wave vectors, they cannot be read out by a single collimated beam unless the hologram is thin. For bulk photorefractive crystals, the hologram recorded is usually a volume one. Shift-invariant properties are quite different for the object and the reference planes. Assuming the reference beam and the readout beam are nearly counterpropagating, as the object image is spatially shifted inside the object plane,

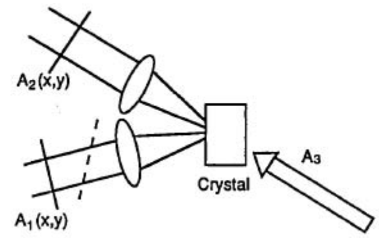

Fig. 1. General architecture of the photorefractive joint-transform correlator.

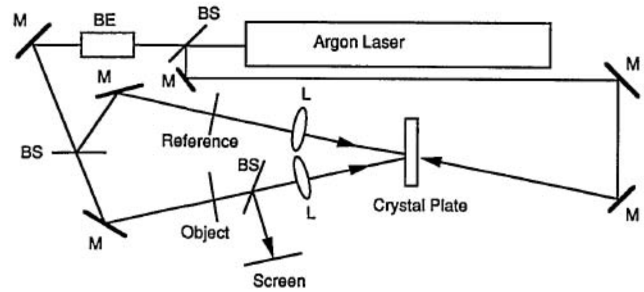

Fig. 2. Experimental setup: BS, beam splitter; BE, beam expander; L's, lenses; M's, mirrors. The photorefractive crystal is a 48-μm-thick Fe:$LiNbO_3$ plate.

the new gratings written by the object and the reference waves are always nearly satisfying the Bragg conditions for the fixed readout beam. Relatively large shift invariance is expected in the object plane, which has been experimentally demonstrated by Nicholson *et al.*[7] For the reference plane, however, the shift invariance becomes much more stringent. This is because, when the reference image is shifted horizontally inside the reference plane, the newly formed gratings tilt away from the fixed readout beam, introducing a phase mismatch in the diffraction process. Thus the correlation signal decays rapidly unless the readout beam adjusts accordingly, as suggested by Gu *et al.*[10] The lack of shift invariance in the reference plane imposes a critical alignment requirement for displaying the reference images and the restricted field of view of the optical correlator. To increase the tolerance of phase mismatch in the diffraction process, we may take two approaches. One is to decrease the carrier frequency, i.e., the angle between the object and the reference beams, since the angular selectivity of the transmission grating is inversely proportional to the spatial frequency of the grating. This approach has been demonstrated by Yu *et al.*[9] The other effective approach for improving the shift-invariant property is to use thin photorefractive crystals so that the diffraction is near the Raman–Nath regime; then the hologram can be read out regardless of the nature of the images. For applications that require high resolution and complex images, we need high carrier frequencies (i.e., a large angle between the object and the reference beams) to accommodate the large field of view. Thin photorefractive crystal plates, which operate in the Raman–Nath regime, are ideal for shift-invariant image correlators. To achieve significant diffraction efficiency of the thin samples, we propose the use of heavily doped photorefractive crystal plate.

The experimental setup is shown in Fig. 2. A collimated beam from an argon-ion laser of 514.5 nm with extraordinary polarization is split into two beams. They are expanded to approximately 9 mm in diameter, and each is spatially modulated by a transparency. The object image contains two lines of charcters, UCSB and OPTICS. The reference image is the letter C. The size of the letters is 1.5 mm. These two transparencies are located in the front focal plane of the Fourier-transform lenses with a focal length of 150 mm. The intersection angle between the object and reference beams is ~17°. A highly doped photorefractive Fe:$LiNbO_3$ thin crystal is placed in the rear focal plane of the transform lenses. The thin sample of 48 μm thickness is polished on both surfaces and attached to a glass substrate by optical cement. The photorefractive grating is read out by a collimated beam counterpropagating with respect to the reference beam. The correlation signal is recorded by a camera or a photodetector by means of a beam splitter. Figure 3 shows the correlation output of the object and the reference images. It is clear that the autocorrelation of letter C gives the strongest signal, while the cross correlations of letter C with letters O and S give secondary peaks. We test the shift-invariant property of the correlator by translating the reference image horizontally. The correlation is observable over the entire aperture of 9 mm. In Fig. 4 the normalized autocorrelation intensity as a function of the displacement of the reference image is measured and is represented by open circles. With exactly the same setup we replace the 48-μm Fe:$LiNbO_3$ sample by a 1-mm Rd:SBN crystal. The shift invariance is reduced from ~7 mm, measured from the 48-μm sample, to only ~400 μm, as represented by X's in Fig. 4. Therefore with the 48-μm thin crystal the shift-invariance property of the joint-transform correlator has improved by ~20 times, as expected, when compared with the 1-mm photorefractive crystal. The diffraction efficiency of the 48-μm crystal is ~3% as compared with 34% for the 1-mm SBN crystal. Highly improved shift invariance with the thin crystal plate at the expense of reduced diffraction efficiency may be justified when the high sensitivity of detection devices such as CCD cameras is considered. The diffraction efficiency can also be improved by choosing proper crystals and doping. The response time for $LiNbO_3$ crystals is generally slow. However, because of the increased quantum

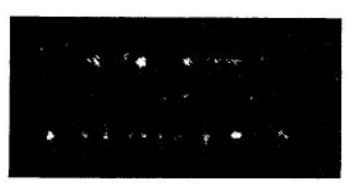

Fig. 3. Correlation image of the letter C with the letters UCSB OPTICS.

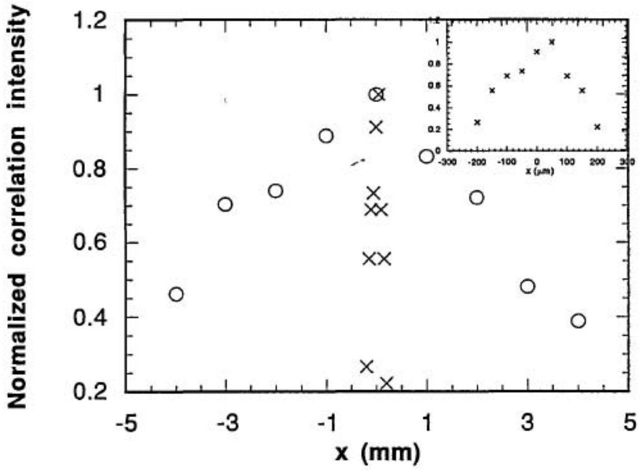

Fig. 4. Experimentally measured normalized autocorrelation intensity as a function of the displacement of letter C (reference image). Circles represent the results from the 48-μm $Fe:LiNbO_3$ sample, and X's represent the results from a 1-mm SBN crystal. The insert is an enlargement of the correlation result from a 1-mm crystal, in which the horizontal axis is in units of micrometers.

efficiency resulting from the heavy doping, a 400-ms response time was obtained in this sample at the intensity level of 2 W/cm^2.

In conclusion, we experimentally investigated the shift-invariant properties of the photorefractive joint-transform correlator. The result shows that the shift invariance can be improved significantly by using thin photorefractive crystals that operate in the Raman–Nath regime of diffraction.

References and Notes

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