High-frame-rate joint Fourier-transform correlator based on Sn$_2$P$_2$S$_6$ crystal

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We present a joint Fourier-transform correlator working at a 10-kHz repetition rate. It is based on a photorefractive Sn$_2$P$_2$S$_6$ crystal operated in the pulsed direct band-to-band photoexcitation regime at a wavelength of 532 nm and a pulse length of 50 ns. The intersection of two plane waves with a total pulse fluence of 100 $\mu$J/cm$^2$ results in a buildup of thin dynamic holograms to a typical diffraction efficiency of $10^{-4}$ in a time of $\sim$1 $\mu$s and decay again in less than 10 $\mu$s. The correlator was tested by a fast image sequence generated by the pulsed readout of a holographic memory system. Successful correlation at a rate of 10 kHz has already been achieved for a pulse energy of only 200 nJ in the template images. © 2001 Optical Society of America

The correlation between two independent input patterns can be implemented very effectively in optics based on the Fourier-transform properties of a lens and a nonlinear optical material. The method proposed by Weaver and Goodman $^1$ in 1966 is called a joint Fourier-transform (JFT) correlator. Intensive investigations to identify the most-suitable nonlinear material for use in a JFT correlator have followed. Those studies included photorefractive Bi$_2$SiO$_5$2–4 LiNbO$_3$5 semiconducting materials,6 multiple quantum wells,7 atomic vapors,8 and liquid-crystal spatial light modulators.9 The potential processing capability of optics is very high because of its large parallelism. However, because of the steady increase in their speed, electronic computers are closing the gap in processing capability. Today, a fast digital signal processor can perform the cascading of the JFT to a holographic memory that delivers the template image sequence allows us to overcome the electronic input device bottleneck and operate the correlator at a rate of 10 kHz.

Sn$_2$P$_2$S$_6$ is ferroelectric below $T_c = 66$ °C (monoclinic point group $m$).10 The optical absorption edge is at $\lambda \approx 533$ nm at room temperature, which, together with a large diagonal electro-optic coefficient of $\sim$60 pm/V,11 makes this crystal well suited for interband photorefraction in the blue-green spectral region. Sn$_2$P$_2$S$_6$ has been also shown to exhibit efficient conventional photorefractive effects in the red–near-infrared range.12 Investigations of the interband effect in Sn$_2$P$_2$S$_6$ were reported in Ref. 16 for the wavelengths 488 and 514 nm. Here the material is characterized at 532 nm.

The absorption of Sn$_2$P$_2$S$_6$ was measured with a Perkin–Elmer A-9 spectrophotometer in a crystal cut along the main axes with the spontaneous polarization nearly parallel to the $ax$ axis. The sample size is $x \times y \times z = 5.6$ mm $\times 5.9$ mm $\times 1.61$ mm, with the polished surfaces perpendicular to the $z$ direction. In our notation the $oy$ axis is perpendicular to the mirror plane as in Ref. 17. The measured absorption coefficients $\alpha$ are 23 cm$^{-1}$ at 532 nm and 0.5 cm$^{-1}$ at 633 nm for $x$-polarized light. For $y$ polarization, one has 7 cm$^{-1}$ at 532 nm and 0.5 cm$^{-1}$ at 633 nm. As the absorption edge is strongly temperature dependent, the crystal temperature $T$ was stabilized by use of an oven. By varying $T$ from 20 to 55 °C, we could tune $\alpha$ for 532 nm from 7 to 120 cm$^{-1}$. This tuning range corresponds to a light-penetration depth $1/\alpha$ ranging from 80 to 1420 $\mu$m; in the absence of optical erasure the resulting effective grating thickness is slightly larger.

Photoconductivity was measured under cw illumination at $\lambda = 532$ nm. The current, $I_{el}$, was...
measured for different light intensities under a field of 200 V/cm (||x axis) applied by means of silver electrodes. The light was incident upon the z surface. At $T = 50\,^\circ\mathrm{C}$ and for a light intensity $l$ larger than 2 mW/cm$^2$ the photoconductivity presents a square-root dependence on $l$, as expected in the case of interband photoexcitation.\textsuperscript{11} For a light intensity of 70 mW/cm$^2$, a conductivity as high as $10^{-4} \, \Omega^{-1} \, \text{m}^{-1}$ was measured, confirming the efficient interband photoproduction of free carriers. The dark conductivity, $\sigma_{\text{dark}}$, is strongly dependent on previous illumination. Maximum $\sigma_{\text{dark}}$ was measured after preillumination with green light (532 nm). In this condition we measured $7 \times 10^{-9} \, \Omega^{-1} \, \text{m}^{-1}$ at room temperature and $9 \times 10^{-8} \, \Omega^{-1} \, \text{m}^{-1}$ at 50$\,^\circ\mathrm{C}$, much smaller than the photoconductivity for an intensity of 20 $\mu$W/cm$^2$.

Holographic gratings were first written by interference of two plane waves (grating vector ||x axis) produced by a Q-switched high-repetition-rate (up to 50-kHz) frequency-doubled Nd:YAG laser ($\lambda = 532$ nm, 50-ns pulse length) and tested under the Bragg angle by use of a weakly absorbed beam ($\lambda = 633$ nm). This geometry is equivalent to the correlator experiment described below if it were to be operated with two point images at the input. We have found the pulsed interband photorefraction in Sn$_2$P$_2$S$_6$ presents a fast buildup time of less than 3 $\mu$s by a pulse fluence of $1-10 \, \mu$J/cm$^2$, a fast decay of less than 5 $\mu$s, a maximum diffraction efficiency of $10^{-4}$ (fluence, $100 \, \mu$J/cm$^2$), and high photosensitivity of $S_1 = (1/\alpha) [\delta(\Delta n)/\delta W_0] = 2.5$ cm$^2$/kJ and $S_2 = \delta(\Delta n)/\delta W_0 = 70$ cm$^2$/kJ, which are among the best reported in photorefractive materials.\textsuperscript{18} $\Delta n$ is the refractive-index change, and $W_0$ is the incident fluence of optical energy per unit area. To avoid distortions of the diffracted beam, possibly induced by mechanical stress produced below the strongly absorbing crystal surface, we had to keep the average intensity below 200 mW/cm$^2$. More-detailed results on the holographic response as a function of the grating period, the pulse fluence, the pulse repetition rate, and the crystal temperature will be reported in the future.

A schematic of the setup of the correlator is shown in Fig. 1. The top left-hand part is a holographic storage memory, and the two arms of the dual-axis JFT correlator can be seen at the bottom. The collimated laser light enters the setup at the top left. The beam is divided by a polarizing beam splitter. The transmitted part is reflected by a galvanic scanner, which is used to produce the reference wave of the angular multiplexed holograms. The other beam is modulated and reflected by a ferroelectric liquid-crystal spatial light modulator (SLM) with 256 $\times$ 256 pixels (Displaytech; pixel size, 17 $\mu$m) that acts as an array of switchable half-wave plates. After modulation, the image beam passes the beam splitter for the second time and is imaged inside the LiNbO$_3$ crystal, which acts as holographic storage medium. A more-detailed description of the writing and high-readout-rate procedure can be found in Ref. 19.

The reconstructed images from the static hologram are used as input templates for the correlator. The beam is deflected by the mirror pair 2–3 and Fourier transformed by lens 11 (focal length $f = 250$ mm). The second input beam of the correlator is derived from the original image beam of the storage system by beam splitter 1. After deflection at mirror 4, the beam is also Fourier transformed by lens 10. We adjust the path lengths of the two arms to produce exactly overlapping Fourier-transform patterns of the input objects on the incidence surface of the Sn$_2$P$_2$S$_6$ crystal. A thick glass plate (25 mm) compensates the 10-mm-thick LiNbO$_3$ crystal and ensures mutual coherence between the waves propagating in the two arms. The gratings written by the input beam are read out with the expanded and collimated beam of a cw He–Ne laser ($\lambda_R = 633$ nm, 10-mW power). The readout angle is adjusted by the mirror pair 5–6 to match the Bragg condition of the grating (3.3-$\mu$m grating spacing) written by the zero-order Fourier components of the input beams. The diffracted readout beam is extracted by use of a dichroic beam splitter and Fourier transformed by lens 12 (focal length $f = 200$ mm) into the correlator output plane. The intensity distribution on the output plane can be detected by a CCD camera, or the central peak can be selected by an aperture and detected with a photomultiplier.

The system is operated in two steps. First, the images are stored in the LiNbO$_3$ crystal by incremental recording.\textsuperscript{20} Second, the object beam is stopped by shutter 2, and the image that is to be correlated with the stored images is displayed on the SLM. The correlation between the input wave from the SLM and the readout wave from the holographic memory will build up in the output plane. We produced high-speed image sequences by reading out ten phase-modulated pictures at a rate of 10,000 frames/s from the holographic memory. These images were extracted from the series “Metamorphosis II” by M. C. Escher.\textsuperscript{21} The total energy of the image sequence that was incident upon the Sn$_2$P$_2$S$_6$ crystal was 200 nJ per image, whereas the pulse energy coming from the

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**Fig. 1.** Schematic representation of the setup. See text for description.
SLM was 800 nJ. The polarization of the beams was vertical, and $T = 27\, ^\circ C$. One can deduce an approximate grating thickness of 560 $\mu$m for such conditions. The intensity of the correlation peak was selected by use of a pinhole. An example of the time dependence of the diffraction efficiency is shown in Fig. 2. The correlation peaks can be clearly identified. Peak 3 is the highest and corresponds to the correctly identified image 3, which was displayed on the SLM. Note that here the diffraction efficiency is lower than that obtained in the plane-wave experiments mentioned above. The main reason is the much lower pulse energy arriving at the Sn$_2$P$_2$S$_6$ crystal in the present experiments. The contrast between the peak heights corresponding to the matching images and those corresponding to the nonmatching images is also lower by approximately a factor of 10 with respect to the expectations for a perfect correlator. The reason is mainly related to the limited usable aperture (4 mm $\times$ 4 mm) of the available Sn$_2$P$_2$S$_6$ crystal, which acts as spatial low-pass filter on the input images. The height of the correlation peak was in fact particularly low for input images showing high spatial frequencies, such as image number 0. The spatial bandwidth is expected to be dramatically improved by use of a high-quality 10 $\times$ 10 mm aperture crystal.

An important figure of merit for light-driven SLMs is the switching energy per pixel, defined as the total energy on the Sn$_2$P$_2$S$_6$ sample divided by the number of image pixels. This energy is $\sim 15$ pJ per pixel for our correlator and is close to the best values found previously for semiconductors, multiple quantum wells, and interband-operated KnB$_2$O$_5$ devices.

For correlators, in addition to the switching energy, the minimum energy required for detection has to be considered. For a diffraction efficiency of 10$^{-7}$ and a detection time of 10 $\mu$s, the input power required for collection of 1000 photons is 5 mW. For pulsed read-out, this minimum energy is reduced to a pulse energy as low as 50 nJ.

In conclusion, pulsed interband photorefractive in Sn$_2$P$_2$S$_6$ allows one to build a joint Fourier-transform correlator operating at a speed of 10,000 frames/s. This is to our knowledge the highest correlation rate ever demonstrated in a photorefractive JPT correlator at visible wavelengths.

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