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Optical pattern recognition system using optical "multiple correlators"

Optical pattern recognition system based on optical "multiple correlators"[1,2] has now being developed to the point where a real-world scene can be processed successfully. The system has a superior ability to perform pattern discrimination: for example, it can discriminate 10^{30} kinds of patterns when 100 multiple correlations are used in the system. This discrimination ability makes it possible to detect targets even if an input image includes many unknown images such as background or noise.

The final goal of our research work is to create an intelligent vision system for a robot or a machine that can aid or monitor the safety of a human by seeing and understanding local circumstances.

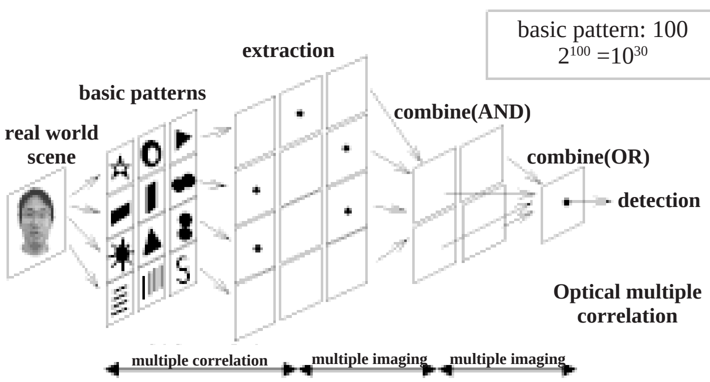

Figure 1. Basic concept of the pattern discrimination algorithm based on multiple correlations.

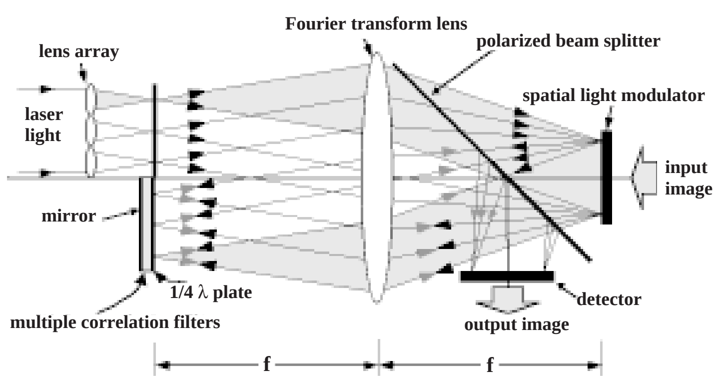

Figure 2. Optical system for pattern discrimination based on multiple correlations.

Real world target detection

Real-world scenes are difficult when it comes to pattern detection: (1) locations and number of targets are unknown a priori, (2) contrast or brightness of the input image is not uniform, (3) a target shape changes according to the view angle, and (4) many unknown images, such as noise or background, are included in the real world scene. Therefore, real-world scenes require image processing techniques that are robust in the presence of such problems.

Conventional optical systems based on a single correlator cannot achieve this robustness because, in most cases, a single correlation process produces many false results caused by unexpected images.[1,2]

The basic algorithm for pattern discrimination based on multiple correlations is described in Figure 1.[2] The correlation process detects which basic patterns are included in an input image. It is the combination of basic patterns extracted that allows the input image to be identified.

If we use 100 kinds of basic patterns, this system can identify 2^{100} kinds of images: nearly 10^{30}. This ability to discriminate between such a large number of images makes it possible to detect target patterns without false positives even if an input image contains unexpected elements.

Optical system

The optical system illustrated in Figure 2 can perform the pattern discrimination algorithm based on multiple cor-

continued on p. 5

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Ultrafast optical 2D-space-to-time-to-2D-space conversion system based on spectral holography

Ultrashort pulse laser technology has advanced rapidly and has now been applied to various fields including optical communication. In particular, various applications based on time-space conversion are being investigated.[1-3] To apply this attractive concept to optical information processing, we have proposed a new technique for ultrafast optical conversion from 2D-space, to time, and back again. This technique can perform ultrafast conversion among both image and time-sequential signals,[4] and aims at the fusion of optical communication and optical information processing. For optical implementation, spatial light modulators play an important role in the interface between the time domain and space domain. Here, we describe one approach to an optical 2D-space-to-time-to-2D-space conversion system based on spectral holography.[5]

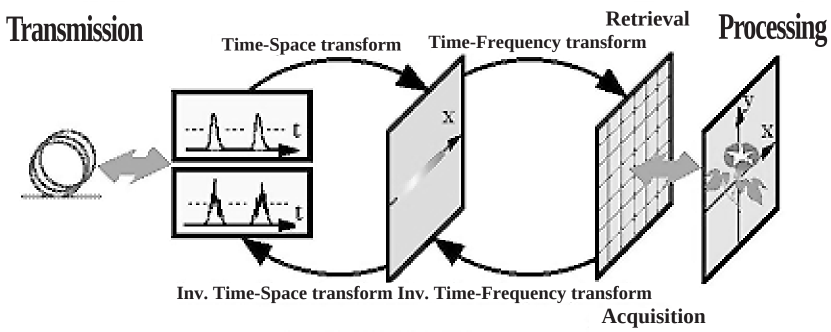

Figure 1. A conceptual diagram of the proposed technique for the ultra-fast, optical, time-to-2D-space-to-time-to-2D-space conversion.

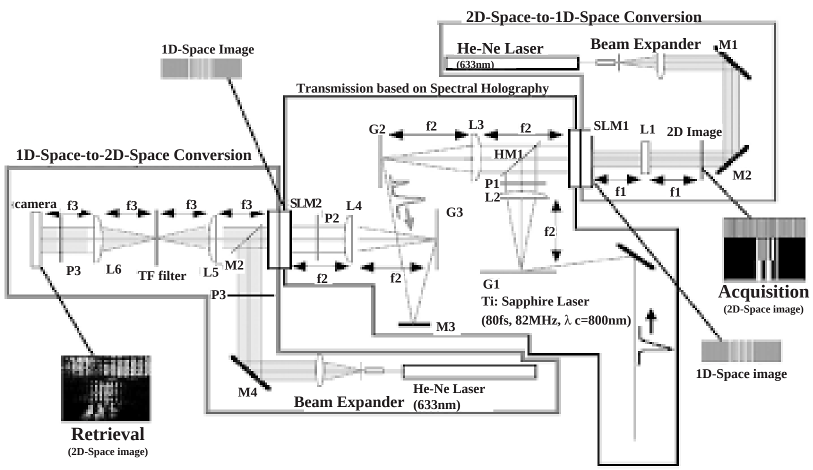

Figure 2. A schematic diagram of the experimental system.

Figure 1 shows a conceptual diagram of the proposed technique. In order to convert a temporal signal into a 2D spatial signal, we only execute the time-space conversion and the time-frequency transform, sequentially. The temporal signal, once converted, can be transmitted by optical fiber. The inverse is carried out by simply performing the same procedure in reverse.

Since each process in the proposed technique can be executed either in the space or time domain, we have different approaches to implementation that we choose as needed. The time-frequency transform and its inverse play important roles of the conversion between the 1D-signal and 2D-signal in our proposed technique. They can be realized by using a simple optical 1-D filtering system. However, such a system has a major disadvantage: optical power loss at the filters. To solve this problem, we propose a new architecture in which this filtering procedure is separated from the others.

Experimental Verification

We constructed an experimental system to verify the proposed architecture. Figure 2 shows the schematic diagram of the experimental system, composed of the 2D-space-to-time conversion section, a transmission section, and the time-to-2D-space conversion section. In the conversion sections, He-Ne lasers are used as light sources whereas, in the transmission section, a Ti:Sapphire laser is used as a source of ultrashort light pulses. In this system, we use a parallel-aligned nematic-liquid-crystal spatial light modulator (Hamamatsu photonics PAL-SLM) as an optically addressable spatial light modulator.[6] Since these devices can perform parallel, but not ultrafast, operations, this experiment was intended only to provide a proof of concept.

First, we executed the spatial time-frequency transform in order to convert a 2D spatial signal (the letter "T") into 1D spatial signal in the spatial domain. Second, we recorded the resulting 1D spatial signal using PAL-SLM1. The 1D spatial signal recorded here can be regarded as a spectral hologram. Finally, we transformed the recorded 1D spatial signal into a modulated temporal signal by using a pulse shaper. In this procedure, we were able to amplify the signal by using a second light source. Next, to perform the time-to-2D-space-conversion, the above is carried out in reverse. The result of the experiment is the successful retrieval of the 2D spatial signal.

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Signal processing using nonlinear optical circuits with 2D feedback

A nonlinear optical feedback system (NOFS) with a liquid crystal spatial light modulator (SLM) can produce a rich variety of spatial outputs.[1-3] Because they were generated cooperatively, the patterns observed in many past experiments have been the result of relatively similar operations. More recently NOFS has been investigated for use in turbulence signal generation, image memory, adaptive optics, and interference measurement. To perform optical processing operations such as display, memory, delay, and switching of images, while maintaining the spatio-temporal dynamics, it is important to be able to generate controllable inhomogeneous patterns at a desired position and time and then move them in a desired direction. We are attempting to apply a NOFS to this kind of task. Here, we demonstrate both memory and delay of images made up of one type of controllable inhomogeneous pattern: isolated spots.[3,4]

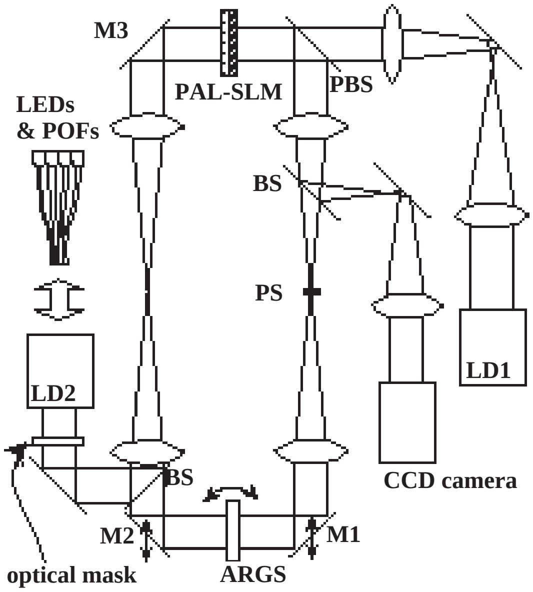

Figure 1. Experimental setup.

Our NOFS is composed of a PAL-SLM (parallel-aligned nematic liquid-crystal SLM, Hamamatsu Photonics K.K.) and the optical feedback is shown in Figure 1.[4,5] The PAL-SLM performs a nonlinear intensity modulation in combination with a polarized beam splitter (PBS).[5] The movements of mirrors (M1 and M2) adjust the focusing condition of the optical feedback. The antireflection-coated glass substrate (ARGS) gives a lateral displacement of the optical feedback in order to perform a self-scanning of the isolated spots. An external signal is given by a laser diode (LD2) and an optical mask, or by light-emitting diodes (LEDs) connected to plastic optical fibers (POFs) arranged in one dimension. The point stop (PS) plays an important role by generating positive or negative spots without any background patterns (such as rolls and/or hexagons). It does this for both in-focus and out-of-focus optical feedback conditions across the entire range of SLM operation.

Figure 2(a) shows how images made up of isolated spots can be "remembered" when the optical feedback is in focus through optical bistability. In order to prevent unwanted spontaneous generation caused by spatial variances in the SLM properties and the readout light intensity, and to prevent shape distortion caused by the anisotropic transverse interactions derived from abberation and slight misalignement, the optical feedback is set so as to be out of focus. Thus the circular spots are triggered only by the external lights as shown in Figure 2(b).

The slight directional emphasis of the transverse interaction leads to the self-scanning of the isolated spots, and a spatio-temporal binary point-oriented image can be recorded. In addition, if we pick out the output at the appropriate position after self-scanning, an image delay is performed,. The delay time is determined by the degree of anisotropy and the readout position. Figure 2(c) shows the self-scanning isolated spots from left to right. The spots (diameter = 50µm) were induced by the temporal sequences of the vertical 1D pattern. The brightest spot on the left side was being recorded on this occasion. The speed of the isolated spots was proportional to the lateral displacement up to ~30µm. At above 33µm, the isolated spots were not sustained.

At present, the temporal resolution is not high, because it is restricted by the response time of the SLM. However, all-optical image memory and delay are indispensable to all-optical information processing. We hope that this method may eventually be used in practice, once combined with high speed devices, such as semiconductor spatial light modulators and broad-area laser diodes.

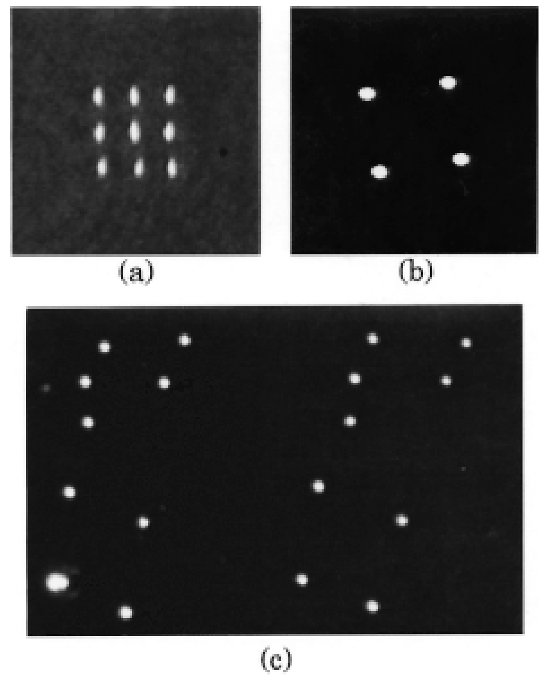

Figure 2. (a) Isolated spots induced by an external 3×3 single-pulsed light source in the in-focus condition. (b) Circular isolated spots induced by a 2×2 single-pulsed light source in the out-of-focus condition. (c) Isolated spot self-scanning from left to right.

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Heterogeneous integration of optoelectronic arrays

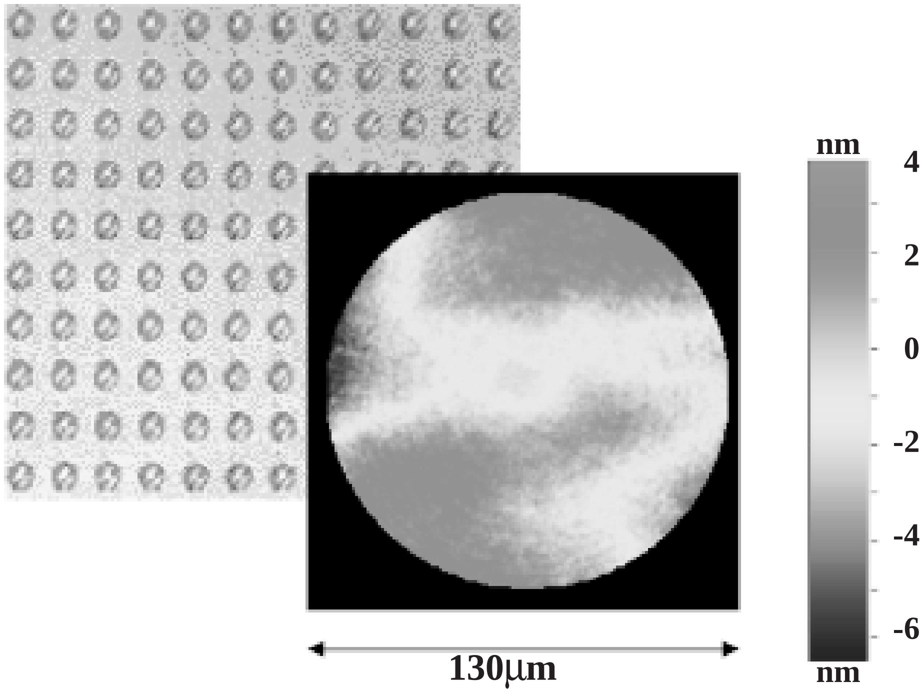

Figure 1. Array of circular microlenses fabricated on SiO_2 substrates and deviation from the spherical of the center 130μm section of a 500μm-diameter lens.

Our group at UCSD is actively involved in basic research aimed towards the development of future generations of integrated optoelectronic array. In the area of near-term applications of optical free-space interconnects to chip-to-chip and board to board communication, UCSD leads the 3D OptoElectronic Stacked Processor (3DOESP) Consortium.

In this project, integrated VCSEL and detector arrays are being developed at the wafer-scale level by Dr. Y. Liu's team at Honeywell Technology Center (HTC) and by Prof. L. Coldren's group at UCSB. HTC's arrays use oxide confined Vertical Cavity Surface Emitting Lasers and MSM detectors operating at 850nm that are further integrated with silicon CMOS chip stacks by flip-chip bonding. The devices are first transferred at the wafer level to a transparent superstrate and the opaque GaAs substrate where the devices are originally grown is removed prior to flip-chip bonding. A 16×16 array is capable of sustaining in excess of 256Gb/s data rates and, within the next year, UCSD, Irvine Sensors Inc., and HTC hope to demonstrate the use of these arrays in actual system prototypes. The arrays developed by UCSB operate at 930nm where the GaAs substrate is transparent and does not require substrate removal. However, to detect the optical signals with acceptable responsivity, the detectors are placed within resonant cavities. Optical channels sustaining 1.5Gb/s have been demonstrated using this approach.

In the longer term, the UCSD group is actively engaged in research to lower the cost of integrated optoelectronic arrays and to remove the limitations imposed by flip-chip bonding. The group's most recent contributions towards this goal include a novel method of integrating high quality lenslet arrays on integrated optoelectronic arrays, and the demonstration of DNA-assisted pick and place of lifted-off optoelectronic components such as LEDs on silicon chips (carried out jointly with Drs. C. Edman and M. Heller from Nanogen Inc.).

One of the important factors limiting the usefulness of optoelectronic arrays is their cost. The wafer-scale fabrication used by HTC is key to this end. However, another cost factor, that of the micro-optical arrays that need to be integrated with the OE arrays, needs to be considered as well. Towards this goal, we are exploring a new means for the fabrication and heterogeneous integration of organic, polymer microlenses with inorganic substrates (including SiO_2, SiN, GaAs, and MEMS devices) using the hydrophobic effect. Although other researchers had suggested the use of the hydrophobic effect to position and fabricate microlenses, this technique had not been evaluated from an engineering point of view. We recently demonstrated the potential of this approach to provide a low-cost, simple alternative to standard microlens fabrication techniques. The key to this new technique is the deposition and subsequent patterning by photolithography of a mono-layer of hydrophobic material on a hydrophilic substrate. The patterned substrate is then immersed in a monomer liquid then pulled out. The monomer liquid is naturally confined to the hydrophilic areas forming small lenslets that are defined by the surface tension. These lenslets are then polymerized under UV exposure and can be transferred to the substrate by reactive ion etching if desired.

Using this technique, UCSD researchers D. Hartmann and O. Kibar have fabricated extremely low-cost high quality microlens arrays (200×200) with diameters ranging between 10-500μm, f-numbers as low as 1.2, and fill factors exceeding 90% with excellent uniformity. More recently, Hartmann has demonstrated the ability to integrate these lenses with MEMS components (jointly with M. Wu's group at UCLA), VCSEL arrays, and optical fiber bundles. The combination of low cost micro-optics arrays such as these with high-performance wafer-scale optoelectronic arrays will be essential for future generations of photonic products.

Jointly with Nanogen Inc., UCSD is also pursuing a novel means of integrating heterogeneous semiconductor materials. The "DNA-assisted micro pick and place" technique utilizes the complementary nature of DNA molecules to provide a means by which micron and nanometer scale devices of entirely different material and origin can be integrated on a single substrate chip in any desired configuration. The procedure requires that short (20 mer) single stranded "capture" DNA molecules are selectively attached to a substrate chip in desired locations. The complementary DNA strands are then attached to devices. When the devices are released in a fluidic solution on the substrate chip, the DNA will tend to hybridize, resulting in the selective attachment of the devices at the desired locations on the substrate. Because DNA carries a net negative charge, this process can be mediated through the application of an electric field, which can assist in moving the devices to the appropriate locations on an

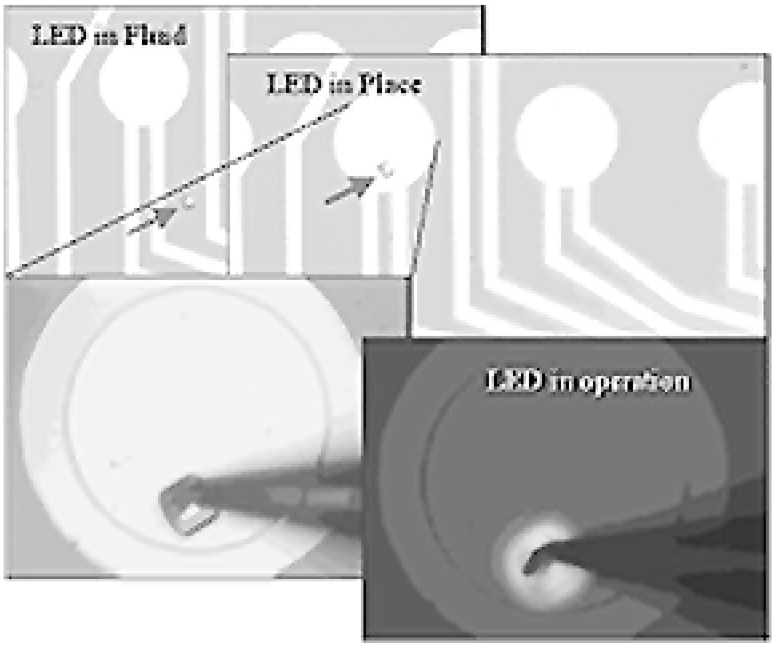

Figure 2. Electric-field-assisted pick and place of an LED. The devices were fabricated in J. Coleman's group at the University of Illinois. Pictures are courtesy of Nanogen Inc.

electrochemical circuit.

In those cases where only one single type of device needs to be picked and placed, the recognition property of DNA is not required and the process can be carried out with components that have been pre-charged, for example, with a suitable detergent material. The feasibility of this "electric-field-assisted pick and place" process has already been demonstrated successfully, and an LED was placed on a silicon chip using this method. Recently, we have also extended our approach to include laser beams for additional local control of the process. The DNA-assisted pick and place approach has excellent potential as a means of heterogeneous integration at the device level, rather than at the chip level, providing a level of flexibility and cost-effectiveness that cannot easily be matched by other techniques.

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Optical pattern recognition

continued from cover

relations.[2] A real-world image is focused onto the spatial light modulator (SLM). Each of the collimated neams generated by the lens array and Fourier transform lens reads an input image out from the SLM. Then, multiple Fourier images of the input appear at the correlation filter plane through the Fourier transform lens and the multiple correlation filters modulate each Fourier image individually. The peaks caused by correlation between the input image and multiple correlation filters are superposed at the detector plane by reflecting the light at the Fourier plane and rotating its polarization using a quarter wave plate. A polarizing beam splitter separates the forward and backward light, directing it away from/towards the spatial light modulator repectively.

A 10×10 lens array used in this optical system allows the performance of the pattern discrimination algorithm with 100 multiple correlations. We are now constructing the optical system in a setup that should end up being about 300mm long and 80mm in diameter. In this design, each lens in the array is 1mm in diameter, the Fourier transform lens (produced by KOSINA Co., Ltd) has a focal length of 80mm, and the spatial light modulator used is a PAL-SLM made by Hamamatsu Photonics K.K.

Evaluation of operating speed

We evaluate the performance of this optical system by comparing it with a digital computer.[2] When the input image size is 512×512 pixels and each correlation filter size is 64×64 pixels, a super computer with 300GFLOPS speed will perform 100 multiple correlations in about 1msec. The optical system can perform the same operation in about 1-10msec when the spatial light modulator has 1-10msec operating speed. This suggests that the optical multiple correlation system may be useful for real-world pattern detection.

This research has been carried out as part of the of the "Tera-optical-information-processing technology" research project promoted by the Japan Science and Technology Corporation.

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Optical wavelet transform using an LCTV-based joint transform correlator

We introduce an optical wavelet transform system that uses the joint transform correlator (JTC)[1] configuration.[2] The system can perform a 2D wavelet transform using a liquid crystal television (LCTV) in conjunction with a CCD camera. A new holographic encoding technique is used to represent positive and negative values of both object signals and wavelet functions. The exact joint power spectrum of object signals and wavelet functions can be obtained via the LCTV with this technique.

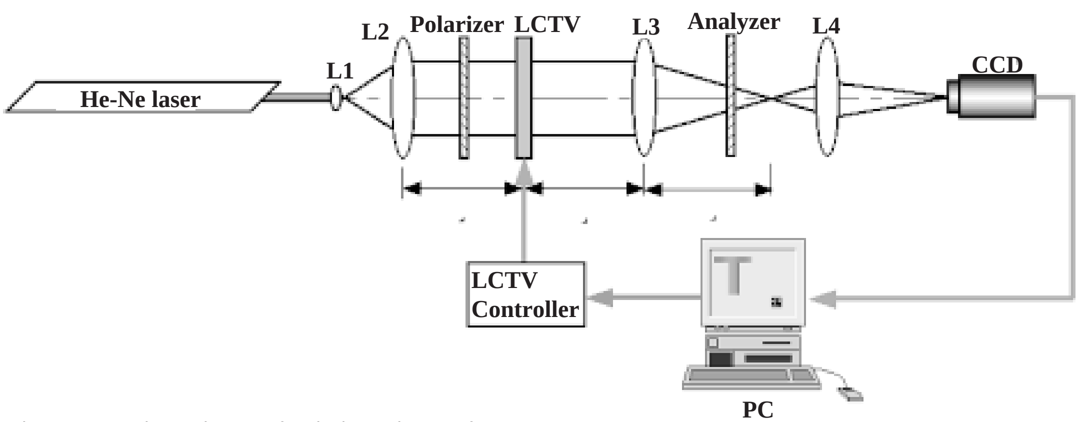

Figure 1. Experimental setup of optical wavelet transform system.

The wavelet transform can be performed by optical correlators.[3] Let the mother wavelet function be $g(x,y)$. Then the daughter wavelet function is defined as

$$g_{a,b,c,d}(x,y) = (ab)^{-1/2} g[(x-c)/a,(y-d)/b], \quad (1)$$

where a and b are scaling parameters, and c and d are translation parameters. The wavelet transform of function $f(x,y)$ is given by

$$WT_{a,b,c,d}=(ab)^{-1/2}\iint f(x,y)g[(x-c)/a,(y-d)/b]\,dx\,dy. \quad (2)$$

Equation 2 shows that the wavelet transform can be optically executed by a cross-correlation operation. The presented optical wavelet system employs a configuration of the JTC that is widely used for optical cross-correlators.

Figure 1 shows a schematic diagram of the presented optical wavelet transform system that is based on the JTC and consists of both optical and electrical devices. An object signal and a wavelet function are encoded by the computer, and displayed on the LCTV, which is illuminated with collimated He-Ne laser light. The wavelet function and the signal are Fourier transformed by lens L3. The joint power spectrum is magnified by lens L4 and then captured by the CCD. By sending the joint power spectrum back to the LCTV, the amplitude transmittance of the LCTV is proportional to the intensity of the joint power spectrum. When the LCTV is illuminated again, the wavelet transform can be obtained by the CCD.

The holographic encoding[4] of object signals and wavelet functions is the key to realizing the present LCTV-based wavelet processor. A real input signal $h(x,y)$ of a two-dimensional position (x,y) is decomposed into two components as

$$h(x,y) = h_+(x,y) - h_-(x,y), \quad (3)$$

where

$$h_+(x,y) = |h(x,y)| \text{ and } h_- = 0 \text{ when } h(x,y) \geq 0$$
$$h_+(x,y) = 0 \text{ and } h_- = |h(x,y)| \text{ when } h(x,y) < 0. \quad (4)$$

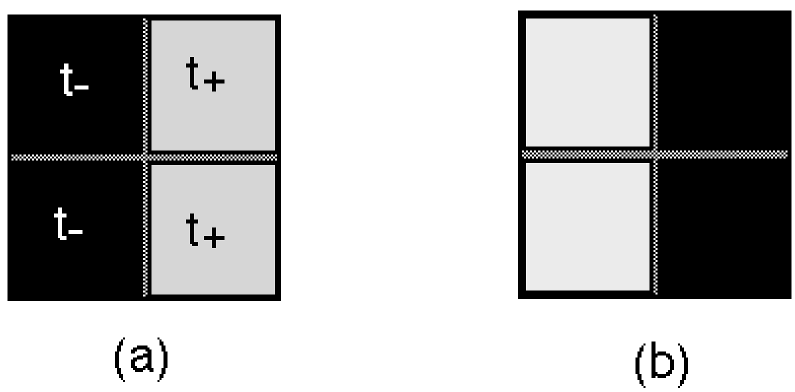

Figure 2. Cell structures: (a) positive and (b) negative signals.

Figure 2 shows the cell structure of two components on the LCTV: the cell consists of four pixels. The transmittance of only two pixels in each cell is modulated by the encoding. When a positive signal is given $(h(x,y) \geq 0)$, it is fed to a pair of pixels as shown in Figure 2 (a). Transmittance $t_+(x,y)$ of the right two pixels is proportional to the magnitude of the signal and the left two pixels are kept opaque. When the signal is negative, it is encoded as shown in Figure 2 (b). Transmittance $t_-(x,y)$ of only the left two pixels is modulated to be proportional to the magnitude of the signal. We then describe the relationship between the intensity distributions in the input plane and the Fourier-transform plane. Let $\partial(x,y)$ be the two-dimensional Dirac delta function. The sampled transmittance $h_s(x,y)$ of the LCTV is given by

$$h_s(x,y)=\Sigma\Sigma\,[h_+(x,y)\partial(x-mw,y-nw) + h_-(x,y)\partial(x-mw+w/2,y-nw)], \quad (5)$$

where m and n are integers, and w is the size of a square cell. By performing the Fourier transform, we obtain a diffraction pattern $H_s(\mu,n)$ as

$$H_s(\mu,n)=\Sigma\Sigma\,[\{H_+(\mu,n)+H_-(\mu,n)\exp(\pi ik)\}*\partial(\mu-k/w,n-l/w)], \quad (6)$$

where k and l are integers, $H_s(\mu,n)$, $H_+(\mu,n)$ and $H_-(\mu,n)$ are the Fourier transforms of $h_s(x,y)$, $h_+(x,y)$ and $h_-(x,y)$, respectively, the asterisk indicates the convolution integral, and (μ,n) are the coordinates of the Fourier-transform plane located at the surface of the CCD. When the first-order diffraction $(k=1)$ is chosen, its amplitude distribution is equivalent to the Fourier transform of $h(x,y)$.

Figure 3 shows the encoded images of the Haar wavelet function and the input signal (capital letter T). The holographic encoding was applied to represent positive and negative val-

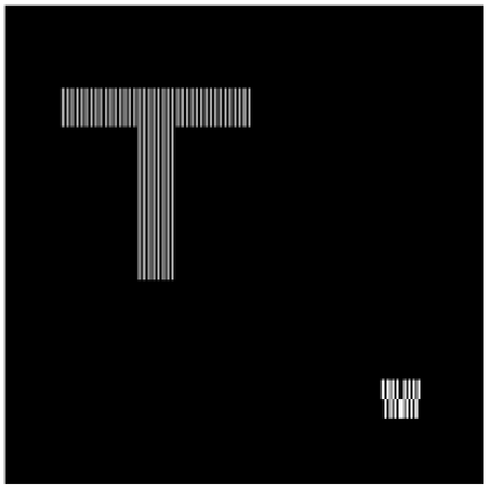

Figure 3. Encoded signal and Haar wavelet function.

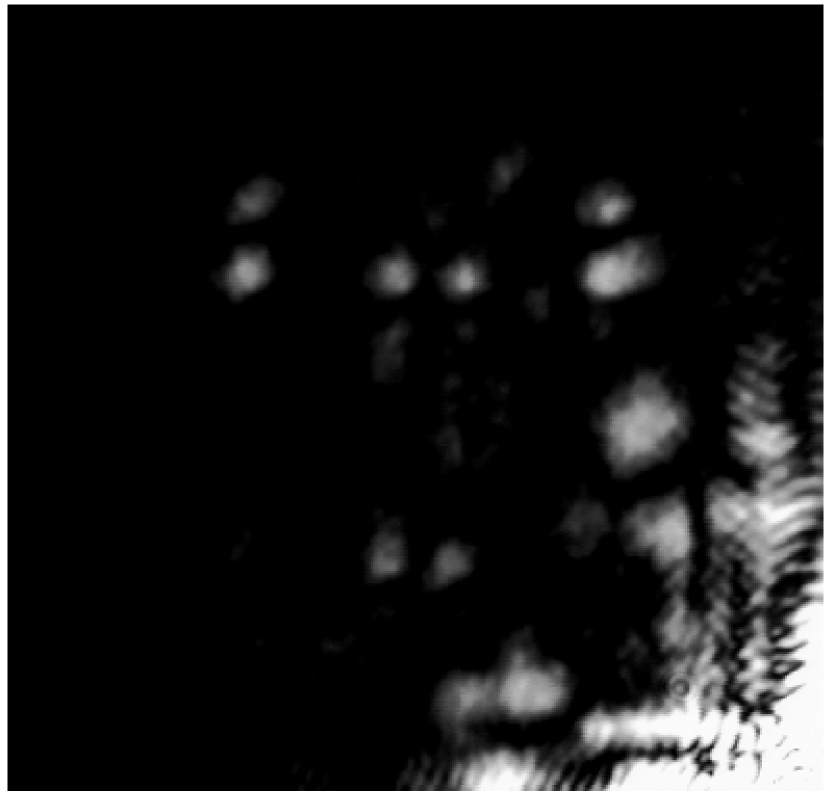

Figure 4. Optical wavelet transform from LCTV based JTC.

ues of both the input signal and the Haar wavelet function. In the experiment, the size of encoded images is 512×512 pixels, and the scaling parameters of the Haar function are set to be *a=b=16* pixels. By displaying the encoded image on the LCTV, we finally obtained the wavelet transform as shown in Figure 4. It was noted that corners of the input image are detected by the Haar function. The LCTV used was one driven by polysilicon thin-film transistors. The horizontal and vertical pixel pitches of the LCTV are 42µm.

The suggested encoding scheme is easily realized in real-time by electronically performing logical AND operation between the input signals and a memorized vertical fringe pattern. In addition, the encoding technique prevents the joint power spectrum from overlapping with the inherent diffraction that is produced from periodic pixels of the LCTV. The joint power spectrum is produced at the middle position between 1st and 0th diffractive orders.

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Polarization encoding for optical security system

Optical validation and security verification methods using optical correlation systems have been proposed. We present one that uses polarization encoding. In this method, a grayscale image such as a face or a finger print is bonded to a polarization-encoded mask. The mask consists of randomly-oriented linear polarizers and can provide an additional degree of freedom in securing information by combining it with a phase code.[1] We call this composite image the polarization-encoded image. In general, this looks the same as the original image because the polarization state cannot be detected by an intensity sensitive detector such as a CCD camera.

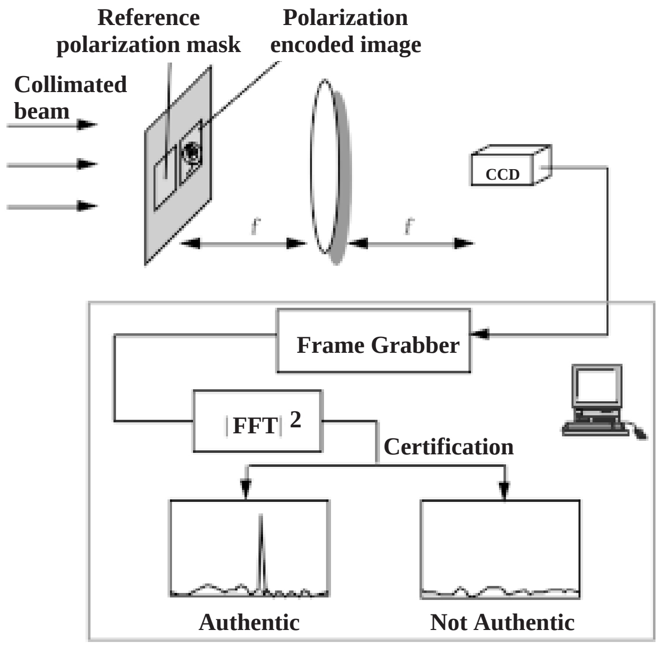

Figure 1. Polarization-encoded optical verification system using a joint transform correlator.

To verify a polarization-encoded image, we optically compare the polarization-encoded image with the reference polarization mask. We use a nonlinear JTC optical system[2] for verification. The polarization-encoded image and the reference polarization mask are placed side-by-side in the input plane of the correlator. The same polarization components between the polarization-encoded image and the reference polarization mask are optically interfered. The joint power spectrum of the two is nonlinearly transformed, to provide a high degree of discrimination, then inverse Fourier transformed. Finally we obtain the correlation between the polarization-encoded image and the reference polarization mask. When they are the same, a strong correlation is produced. When the two masks are different, the correlation signal is lower. Thus, we can verify the image in terms of the correlation between the polarization-encoded mask and the reference polarization mask.

We performed computer simulations in which the image and a polarization masks consist of 128×128 pixels. The polarization-encoded image and the reference polarization mask are place side by side at the JTC input plane consisting of 512×512 pixels. The correlation output obtained by a binary JTC is shown in Figure 1. The bottom left of Figure 1 illustrates the case where the reference polarization mask is the same as the encoding polarization mask, whereas the bottom right shows the case when the reference mask is different from the encoding mask. It is clear that the correlator has verified the authentic polarization-encoded image and rejected the unauthorized image.

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Reconfigurable free-space

continued from back cover

cal interconnection module is acting as the interface between two optoelectronic processor arrays. Since the interconnection topology and the functionality are fully programmable, we could distribute optimum processing and communication loads among the layers of the processors to get the computational maximum efficiency. Global interconnectivity is also achievable since the communication channels are constructed via optical paths in free-space. Optical paths in OCULAR-II can efficiently implement data transfer between distant processors.

As for the PE array with parallel photodetectors, a 64×64 version has been successfully fabricated. We are also trying to build more compact optical systems.

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Liquid-crystal spatial light modulator for phase-only modulation

Two-dimensional phase-only light modulation has drawn a great deal of interest in applications for optical correlation,[1] optical interconnection,[2] phase-contrast techniques,[3] adaptive optics[4] and so forth. We have developed a unpixelated, optically-addressed, parallel-aligned nematic-liquid-crystal spatial light modulator (PAL-SLM)[5] in order to make these applications practical. The electro-optical characteristics of the parallel-aligned nematic-liquidcrystal layer allow a large depth of phase-only modulation.

Further, a phase-only modulator must be controllable by a computer for the real-time display of computer-generated patterns. One practical way of doing this is to use a liquid crystal display or LCD as an accurate, addressable mask for the PAL-SLM. We have developed a two-dimensional, electrically-addressed phase-only light modulator module by combining the PAL-SLM and the LCD with optimized optics,[6] and have used these spatial light modulators for several applications.

The PAL-SLM has a sandwich structure consisting of an undoped hydrogenated amorphous-silicon (a-Si:H) photoconductive layer (used for addressing), a dielectric mirror, and a parallel-aligned nematic-liquid-crystal layer for modulating between the two transparent conductive electrodes (ITO), as shown in Figure 1. By illuminating the a-Si:H layer with "write" light, voltage is supplied to the liquid crystal layer. This causes the liquid crystal molecules to tilt and the readout light is modulated, in parallel, corresponding to the write-light information. The phase shift of over 2π radians (at 680nm) can be accomplished with write-light intensity of 200W/cm^2 (at 680nm) when the applied voltage is 3.0V. Here, the readout laser light is polarized parallel to the molecular axis of the liquid crystal. The response time was measured at be 30msec, for a phase-modulation depth of π radians.

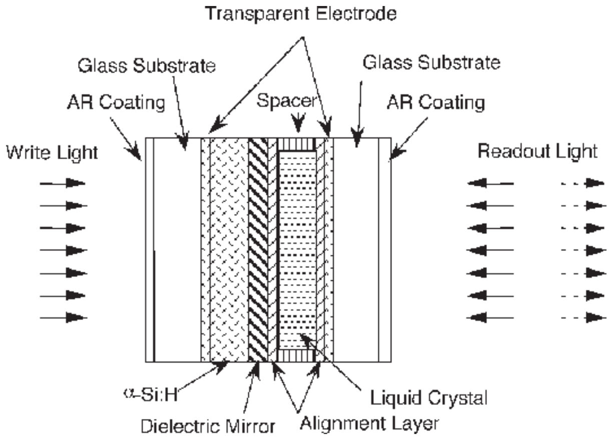

Figure 1. Structure of the PAL-SLM.

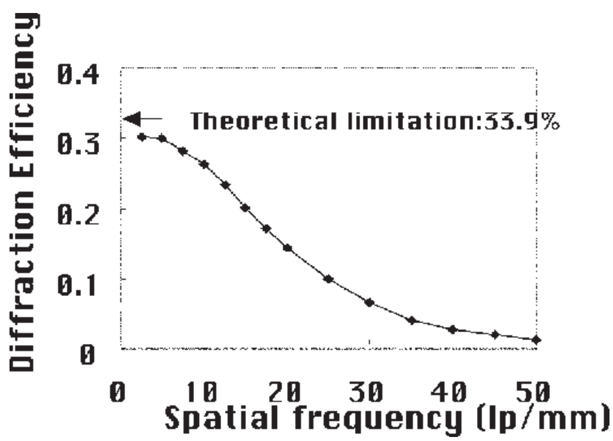

Figure 2. Diffraction efficiency of the PAL-SLM.

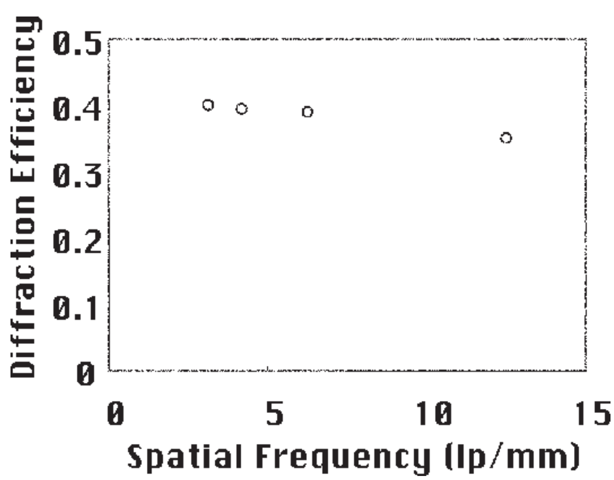

Figure 3. Diffraction efficiency of the LCD coupled PAL-SLM.

Figure 2 shows the diffraction efficiency of the device. At low spatial frequencies (<5 line pairs/mm), the diffraction efficiency was 31%, which was very close to the theoretical maximum of Raman-Nath diffraction (33.9%).

The LCD (640×480 pixels) and the PAL-SLM were coupled by a set of lenses for 1:1 imaging. We designed an optical system that would not transfer the pixel structure of the LCD, thus preventing the noise diffraction it would cause.

The transfer characteristics were measured. Uniform patterns of each gray level were displayed on the LCD and the amount of PAL-SLM phase modulation was measured as a function of grey level. The relation between them was almost linear and more than 2π -radian modulation was achieved.

The diffraction efficiency of the device was also measured as shown in Figure 3. Binary intensity gratings of vertical line were displayed on the LCD. More than 35% of diffraction efficiency was obtained even when the spatial frequency was 480 TV lines.

We have applied these spatial light modulators to an optical correlator for fingerprint identification,[1] displacement measurement,[7] phase contrast techniques,[3] and optical interconnection[2] using a reconfigurable computergenerated hologram.

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Reconfigurable free-space optical interconnection module

We have realized a reconfigurable free-space optical interconnection module that connects VLSI chips with parallel optical input and output (I/O) channels.[1] The interconnection topology is reconfigurable by modifying a computer generated hologram (CGH) written on a parallel-aligned nematic liquid-crystal spatial light modulator (PAL-SLM), developed by Hamamatsu Photonics K.K., and located at the Fourier plane of the module. The appropriate interconnection topology can therefore be built to meet the requirements of a given application. For example, a pixel can be made to transmit data to several pixels simultaneously if a fan-out diffraction pattern is written into the phase modulation at the Fourier plane. Such a pipelined parallel optoelectronic processing system has been combined with processor arrays, yielding a processing capability that does not suffer from the usual data-transfer bottlenecks. This is thanks to the dense interconnection bandwidth supplied by the optical interconnect.

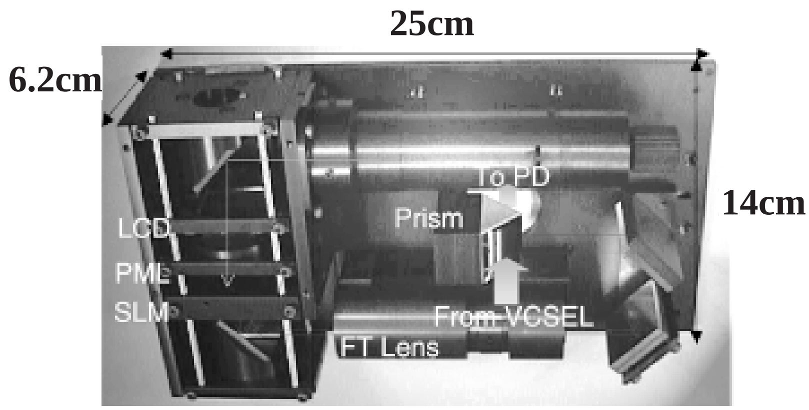

Figure 1. Optical interconnection module.

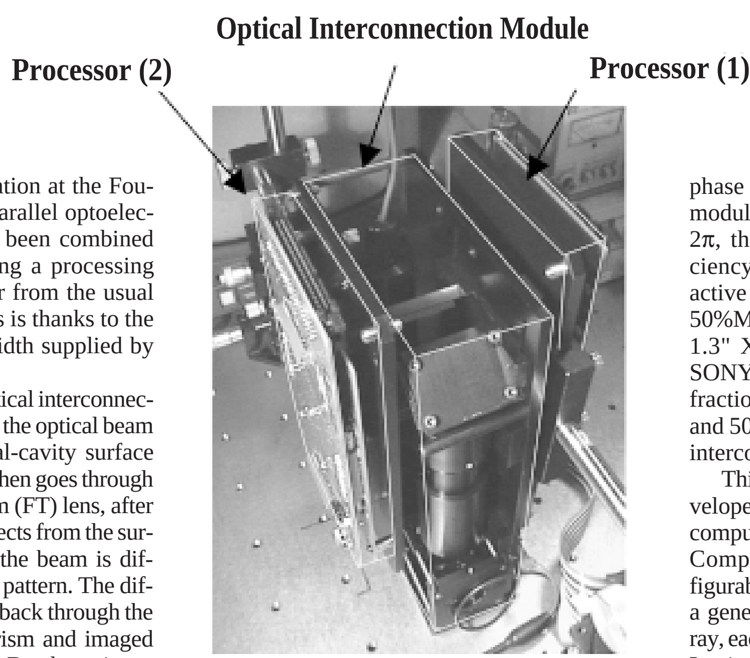

Figure 2. Two-layer pipelined system.

Following it through the optical interconnection module shown in Figure 1, the optical beam is first generated by a vertical-cavity surface emitting laser (VCSEL) array, then goes through the prism and Fourier transform (FT) lens, after which the collimated beam reflects from the surface of the PAL-SLM where the beam is diffracted depending on the CGH pattern. The diffracted optical beam then goes back through the FT lens, is reflected by the prism and imaged onto the photodetector array. By the using a prism in a reflection-type configuration, the input and output surfaces are located on opposite sides. The result, therefore, is pipelined and stackable. The focal length of the FT lens is variable, ranging from 360mm to 440mm to compensate for temperature fluctuations and to ease the alignment. To make the module compact, the FT lens is shared for input and output and is implemented in a zoom lens configuration to shorten the working distance (155-200mm). In addition, the optical path is folded by mirrors several times for compactness and modularity. The PAL-SLM is addressed by a compact liquid crystal display (LCD) panel that is illuminated by a visible laser diode. The LCD and the PAL-SLM are coupled by a planar micro lens (PML) array with a working distance of 32mm. The size of the module overall is 250mm×140mm×62mm.

A key component of the unit is the PAL-SLM used as a 2D optical phase modulator, which consists of a-Si layer for optical addressing and a liquid crystal layer for phase modulation. This device is capable of modulating the phase of the light beam beyond 2π, thus enabling excellent diffraction efficiency. The PAL-SLM has a 20mm×20mm active area with a resolution of 20 lp/mm (at 50%MTF). The LCD used is a 1024×768-pixel 1.3" XGA-LCD (LCX023BL, produced by SONY) with a 26μm horizontal pitch. The diffraction efficiency resulting is between 10% and 50% of the ideal value and depends on the interconnection pattern.

This optical interconnection module was developed for a pipelined parallel optoelectrnic computer called OCULAR-II (Optoelectronic Computer Using Laser Array with Reconfigurability).[2] Each processing layer consists of a general purpose processing element (PE) array, each "pixel" of which contains an Arithmetic Logic Unit (ALU), local memory, 4-neighborhood connections, and optical I/O channels. Figure 2 shows a two-layer system where the opti-

continued on p. 8

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