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Optical computing using hybrid encoded shadow casting

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The parallel processing property of optics has been recognized as the main driving force behind digital optical computing.[1,2] A parallel pattern logic operation, first proposed by Tanida and Ichioka,[3,4] overlaps spatially coded 2-D binary pixel patterns situated in an optical input plane. These patterns, when illuminated by divergent light beams emanating from a group of LEDs, form different interlaced projections (shadows) representing different parallel logic operations in the optical output plane. Since the pattern overlap corresponds to a spatial domain filtering process, it is also known as optical shadow casting (OSC). Using OSC, a large number of 2-D binary[3,4] or multiple-valued[5,6] logic inputs can be parallel processed. Another pattern logic method, proposed by Bartelt *et al.*,[7] uses theta modulation to encode the signal grey-level values into different grating orientations. The combination of these grey-level-dependent gratings form the logic inputs that are to be manipulated by a coherent optical processor. Using spatial-frequency domain filtering, different optical logic functions can be generated. Recently, Yatagai[8] described another pattern logic method in which the spatially encoded patterns are overlapped with an operational mask. Instead of using the OSC LED patterns, this method switches an operational mask for the different logic operations. However, in all these pattern logic methods, either the spatial filtering or pixel casting process is performed by either a transparent or opaque screen. In this communication, the use of a polarization encoding and filtering method to perform lensless OSC logic operations is proposed. Both linear orthogonally polarized and hybrid form polarizations with transparent/opaque mask input, logic signals are used. Using this polarization or hybrid encoded OSC (POSC), double- or triple-instruction logic operations can be performed. This technique can be extended to generate multivariable binary as well as two-variable multiple-valued logic functions and can also be used in conjunction with the Yatagai's pattern logic method. Pertinent examples such as the design of a binary full- and a ternary half-adder are presented.

In the proposed POSC, while the geometry is identical to the conventional lensless OSC, the logic inputs and outputs are represented by the sense of polarization. Take the two-variable (A and B) binary logic as an example (see Table I). These variables are represented by the two polarization encoded masks (the second and third columns of Table I), where the symbols — and | denote the two linear, parallel and perpendicular, polarizations representing the physical x and y directions, respectively. The two thus encoded input masks (see the fourth column of Table I where $\wedge$ denotes the overlap) are illuminated by a group of four nonpolarized LED sources. When three of the four LEDs (see the first column of Table I) are on, corresponding to four overlapped input patterns, on the output screen four different projections are formed. In each of the four cases, two cross-polarized light patterns can simultaneously exist. The $x(y)$-polarized output plane center cell pattern corresponds to the logic operations A NAND B (A OR B), respectively. Thus a fixed LED source pattern and the rotation of the output center-cell polarizer allow the implementation of two different binary logic functions. By removing the output polarizer, a third binary function, the superposition of the two cross-polarized patterns, can also be generated. With a OSC, because the opaque part of the screen blocks the light, the mutually transparent part of the overlapped inputs is limited to be only a quarter of the mask area. With a POSC, the mutually transparent input mask area is doubled (with each half transparent to one of the two orthogonal linear polarizations). Therefore, for a fixed source and input pattern, two orthogonal transmission channels exist.

Orthogonally polarizing LEDs can also be used as light sources. In this case, the overlapped transparent masks respond only to $x(y)$-polarized LEDs. Using different combinations of polarized LEDs, different binary logic functions can be implemented. In Table II(a), using either unpolarized on/off or orthogonally polarized input LED states, the generations of all sixteen two-variable binary logic functions

Table I. Example of POSC Input Output Signal as well as LED Source Encodings. The symbols — and | Represent x and y Polarizations, and $\wedge$ denotes the input overlap.

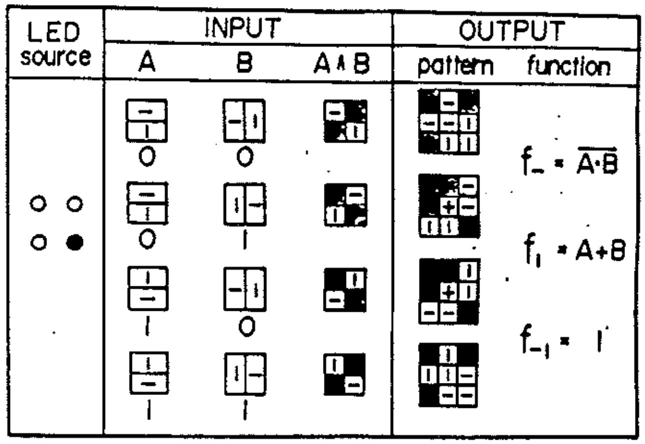

Table II. Sixteen Possible POSC Two-Variable, with Inputs Encoded with Either Variables A and B (a) or variables A and C (b), Logic Operations. Both Transparent/Opaque and Orthogonal Polarization Input LED States are Used.

INPUT A	B
0	0
0	1
1	0
1	1

function mask																
Mask 1	O	AB	$A\bar{B}$	A	$\bar{A}B$	B	$A\oplus B$	$A+B$	$\overline{A+B}$	$\overline{A\oplus B}$	$\bar{B}$	$A+\bar{B}$	$\bar{A}$	$\bar{A}+B$	$\overline{AB}$	I
Mask 2	O	$\overline{A+B}$	$\bar{A}B$	$\bar{A}$	$A\bar{B}$	$\bar{B}$	$A\oplus B$	$\overline{AB}$	AB	$\overline{A\oplus B}$	B	$\bar{A}+B$	A	$A+\bar{B}$	$A+B$	I
Mask 1	O	AB	$A\bar{B}$	A	$\bar{A}B$	B	$A\oplus B$	$A+B$	$\overline{A+B}$	$\overline{A\oplus B}$	$\bar{B}$	$A+\bar{B}$	$\bar{A}$	$\bar{A}+B$	$\overline{AB}$	I
Mask 2	I	$A+B$	$A+\bar{B}$	A	$\bar{A}+B$	B	$\overline{A\oplus B}$	AB	$\overline{AB}$	$A\oplus B$	$\bar{B}$	$A\bar{B}$	$\bar{A}$	$\bar{A}B$	$\overline{A+B}$	O

(a)

INPUT A	C
0	0
0	1
1	0
1	1

function mask																
Mask 1	O	AC	$A\bar{C}$	A	$\overline{A+C}$	$\overline{A\oplus C}$	$\bar{C}$	$A+\bar{C}$	$\bar{A}C$	C	$A\oplus C$	$A+C$	$\bar{A}$	$\bar{A}+C$	$\overline{AC}$	I
Mask 2	O	$\overline{A+C}$	$\bar{A}C$	$\bar{A}$	AC	$\overline{A\oplus C}$	C	$\bar{A}+C$	$A\bar{C}$	$\bar{C}$	$A\oplus C$	$\overline{AC}$	A	$A+\bar{C}$	$A+C$	I
Mask 1	O	AC	$A\bar{C}$	A	$\overline{A+C}$	$\overline{A\oplus C}$	$\bar{C}$	$A+\bar{C}$	$\bar{A}C$	C	$A\oplus C$	$A+C$	$\bar{A}$	$\bar{A}+C$	$\overline{AC}$	I
Mask 2	I	$A+C$	$A+\bar{C}$	A	$\overline{AC}$	$A\oplus C$	$\bar{C}$	$A\bar{C}$	$\bar{A}+C$	C	$\overline{A\oplus C}$	AC	$\bar{A}$	$\bar{A}C$	$\overline{A+C}$	O

(b)

are summarized. For unpolarized LEDs, either output state can be obtained from the other by interchanging (for both variables) the zero and the one logic assignments. For polarized LEDs, the cross-polarized outputs represent positive- and negative-true logic functions, respectively. In addition to the input codes shown in Table I, other input encoding methods where the overlapped input patterns preserve, for the two orthogonal polarizations, the two mutually transparent parts, are also possible. In Table II(b), for the variable C, an alternative input variable encoding is shown. For the variables A and C, the corresponding sixteen logic function generations are also shown. It has been indicated that a conventional single-element OSC processor is a single-instruction multiple-data (SIMD) machine. Using POSC, both double- and triple-instruction logic processing can be performed. If in the previous example we locate three different detectors at the center cell of the output screen, with the first (second) being $x(y)$ polarized, and the third unpolarized, three different functions can be simultaneously processed. Therefore, a single-element POSC represents a multiple-instruction multiple-data (MIMD) machine.

In binary optical computing, implementation of multivariable logic functions are needed. For example, for binary addition, to generate both the output sum and the carry, three variables need to be used. To perform binary OSC addition to preserve symmetry, Kozaitis and Arrathoon[5] have used four rather than three variables. One of the four

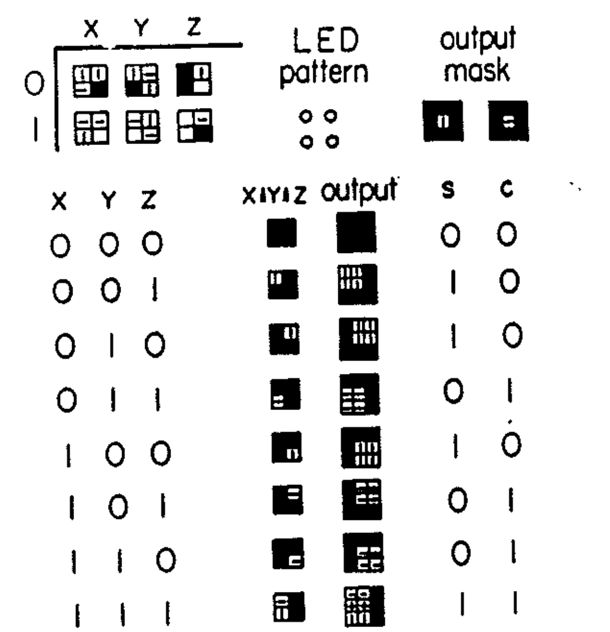

Fig. 1. Single-element POSC binary full-adder. A hybrid input polarized patterns correspond to the sum and carry outputs, respectively.

variables, however, is kept at zero during the operation. With this method, the detectable output signal area is reduced to a quarter of the previously used two-variable area. This size reduction limits, due to diffraction effect, the pixel integration area. To achieve a reasonable output, larger input pixels must be used. The use of POSC leads to larger aperture (identical to two-variable case) three-variable binary logic operations. Using three differently encoded variables A, B, and C [see Tables II(a) and (b)], the overlap among three inputs will always contain a mutually transparent area to either one of the two orthogonal linearly polarized beams. The use of the eight possible input overlaps, together with a group of LEDs, can generate two^8 three-variable binary logic functions. For a one-bit binary full-adder, two parallel POSC elements, one for the sum and the other for the carry, need to be used. Because the POSC is a MIMD machine, using other input encoding schemes, it is possible to perform a single-POSC-element binary addition. For example, in Fig. 1 a single-element POSC binary full-adder is shown. Here the input uses hybrid (both transparent/opaque and orthogonal polarization) codes. In the first four columns of Fig. 1, the input variables X, Y, and Z and their corresponding overlaps are shown. When all four unpolarized LEDs are on, the two cross-polarized patterns in the center cell of the output plane represent the resultant sum and carry bits, respectively. Thus, using two, one x and the other y polarized, detectors at the output center cell, a single-element POSC binary full adder can be constructed.

The similar idea can be applied to two-variable tenary logic computing. For each input variable, three mutually orthogonal states representing the symbols 0.1, and 2, respectively, are required. For the nine possible overlaps among the two ternary input variables, a mutually transparent area must be provided. The use of the two orthogonal polarizations in the four corners of the overlapped pattern produces eight different states. The ninth state is encoded as an unpolarized but transparent corner. As an example, consider the operation of a two-variable POSC ternary half-adder. In Fig. 2, the hybrid form of input variables A and B are shown. Using the input variable truth table (the first two columns) in the third column the nine possible two variable A and B overlap forms are shown. One of the overlap patterns is forced to be opaque. The sum output symbols, 0, 1, and 2, are encoded as opaque y- and x-polarized signals, respectively. Correspondingly, in the fourth column, the LED source and the center cell output patterns are shown. The results, shown in the fifth column, are obtained from the two x- and y-polarized center cell detectors. To generate the carry another POSC cell must be employed. For this carry, in the sixth and seventh columns, the corresponding LED pattern and the output unpolarized detection results are shown.

To summarize, an efficient polarization encoding and filtering method to perform OSC optical computing is proposed. Inputs are spatially encoded with either polarized or both polarized and transparent/opaque pixels. Either polarized or unpolarized LED input source arrays can be used. At the center cell of each output element, depending on different parallel polarization filters, three different logic functions can be obtained. In addition to the two-variable binary. The POSC method is suitable for large aperture multivariable binary and the two-variable ternary optical computing. Using liquid crystal e-o material sandwiched between $\lambda/2$ plates and linear polarizers, real-time polarization encoding can be performed leading to optical parallel processing of a large amount of data.

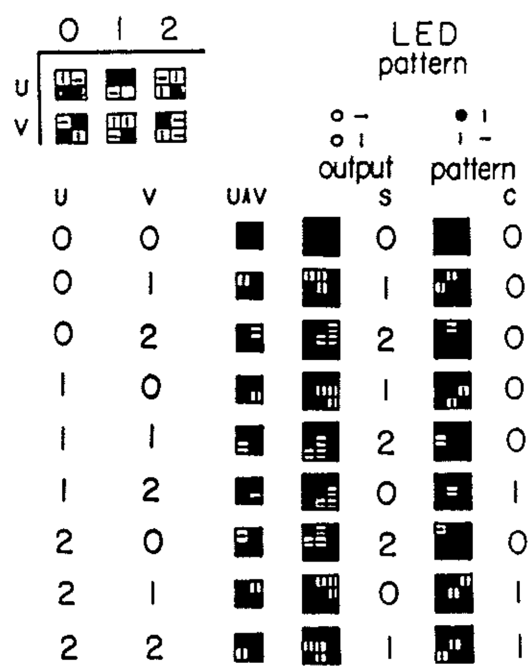

Fig. 2. POSC ternary half-adder. The hybrid input code is used. The output sum symbols 0.1 and 2, are encoded as opaque y and x-polarized signals, respectively. For the carry, both polarizations are used.

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