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Parallel optical logic using optical phase conjugation

George Eichmann, Yao Li, and R. R. Alfano

City University of New York, City College, New York, New York 10031.

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Nonlinear optical phase conjugation (OPC) offers solutions to many problems in real-time optical signal and image processing. In an analog mode, using OPC, optical signals (images) can be processed in parallel.[1] Also, using OPC, digital logic implementation has been suggested.[2] The optical logic variables are represented by either the beam on/off or its orthogonal polarization states. Using these representations, a number of binary optical logic elements such as AND, EOR, NOT, have been described. In this Letter, a new method to perform parallel digital optical logic that combines OPC with parallel logic generation techniques is proposed. This technique is suitable to implement optically all sixteen binary logic operations.

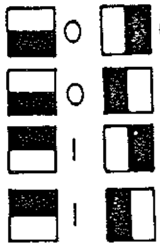
To perform parallel optical logic, Bartelt *et al.*[3] proposed coherent theta modulation, while Ichioka and Tanida[4] (I–T) and Yatagai[5] suggested incoherent geometric optical shadowcasting (OSC) methods. In the following, the use of both OSC schemes is discussed. In both the I–T and Yatagai approaches the logic encoding is identical, with the difference being in how the different logic operations are performed. While I–T uses different LED source patterns, Yatagai uses a switchable operation mask to obtain different logic operations. In both methods, the optical beams must pass three consecutive, either a source and two input or two input and a output mask, planes. This triple-multiplication implies an optical triple-product operation. To perform an optical triple-product operation, one may use acoustooptic Bragg cells,[6] nonlinear third harmonic generation,[7] as well as the nonlinear OPC.[8] Here, we only discuss an OPC parallel optical logic processing method.

An OPC technique based on the use of Yatagai's scheme is described first. In Fig. 1, a typical OPC experimental setup is shown. Three input beams generated from the same laser, labeled E_A, E_B, and E_C, are collimated into a cubic $[\chi^{(3)}]$ nonlinear material (NLM). The beams E_A and E_B are mutually phase-conjugated. The third beam E_C serves as the probe. The nonlinear interaction of the three beams in the NLM generates a polarization source that radiates a fourth beam:

$$E_O \propto \chi^3 E_A \cdot E_B \cdot E_C^*, \tag{1}$$

where the * stands for complex conjugation. In analogy to Yatagai's parallel logic geometry, the two encoded logic input masks T_A and T_B (the encoding and operation schemes for both Yatagai's and I–T's methods are summarized in Table I) are inserted into the path of beams E_A and E_B, respectively, while the operation mask T_C is placed on the E_C beam. The phase-conjugate signal E_O, separated out by a beam splitter, is the logic output. This output beam possesses the same properties as Yatagai's arrangement. Since this OPC geometry is no longer collinear, both input and output beams can be separated either spatially or directionally. This separation allows for the optical interconnection of various stages of parallel logic processors. These processors are needed to perform multiple-instruction multiple-data (MIMD) parallel processing. Also, to generate a phase-conjugate signal, as long as E_A and E_B beams counter-

Table I Optical Encoding (Black/White Code) Techniques for Either the Yatagai- or I-T-Type Optical Parallel Logic Processing

coded inputs A	coded inputs B	logic function	O_0	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8	O_9	O_{10}	O_{11}	O_{12}	O_{13}	O_{14}	O_{15}
 0, 0, 1, 1	0, 1, 0, 1		0	$A\cdot B$	$A\cdot\bar{B}$	A	$\bar{A}\cdot B$	B	$A\oplus B$	$A+B$	$\overline{A+B}$	$\overline{A\oplus B}$	$\bar{B}$	$A+\bar{B}$	$\bar{A}$	$\bar{A}+B$	$\overline{A\cdot B}$	1
		Yatagai operation mask																
		I-T input LED pattern	●● / ●●	●● / ●○	●● / ○●	●● / ○○	●○ / ●●	●○ / ●○	●○ / ○●	●○ / ○○	○● / ●●	○● / ●○	○● / ○●	○● / ○○	○○ / ●●	○○ / ●○	○○ / ○●	○○ / ○○

Both methods use identical input logic variable encoding (see left side). To implement different logic operations, coded operation masks (for Yatagai's method) and coded input LED patterns (for the I–T method) are shown on the right.

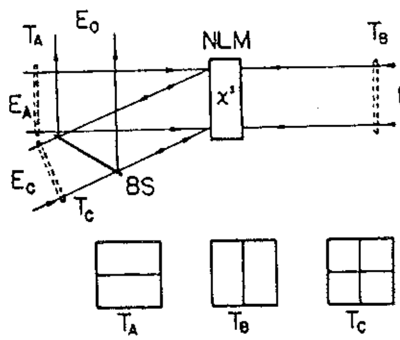


Fig. 1. OPC implementation of a Yatagai-type parallel logic processor: NLM, cubic nonlinear material, BS, beam splitter; E_A, E_B and E_C, collimated input beams; E_O, the phase-conjugate output beam; T_A and T_B, two coded input masks; and T_C, the logic operation mask.

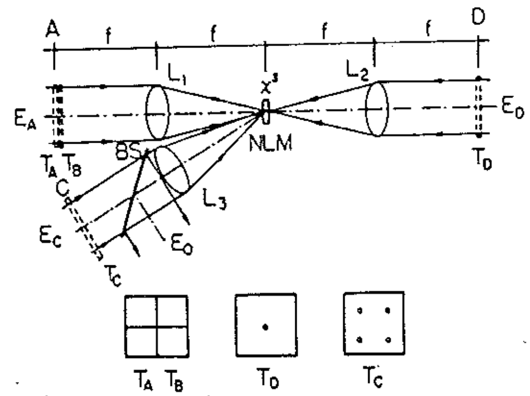


Fig. 2. OPC implementation of an I-T-type parallel logic processor: L_1, L_2, and L_3, three equal-focal-length Fourier transform lenses; BS, beam splitter; NLM, nonlinear material; E_A, E_D, and E_C, collimated input beams; E_O, output beam; T_A and T_B, two coded input masks superposed in the plane A; T_D, a mask containing a central δ-function placed in the plane D; T_C, a logic operation mask placed in the plane C.

propagate (phase-conjugated), the third E_C beam can be incident from any angle. Thus, using different operation masks with various angular probe beams together with an angular multiplexer that selects at a given time a different probe beam, both space- and angle-variant optical parallel processing of large amounts of data are possible. Furthermore, since the OPC is a coherent optical technique, the combination of the OPC parallel digital logic method and other standard coherent optical analog processing techniques can make it a more flexible arrangement.

Next, using the NLM cell as a real-time triple-product operator, an I-T-type parallel OPC logic generation is discussed. As mentioned earlier, to obtain the various optical binary logic operations, the I–T method use an array of switchable LED source patterns. From a geometric point of view, the interlaced output pattern due to the different LEDs can be interpreted as an optical shadowgram. However, this operation is also equivalent to a 2-D optical multiplication followed by a incoherent correlation. It is well known that 2-D coherent optical correlation can be performed using a Fourier transform lens. Based on this concept, in Fig. 2 an coherent real-time OPC correlator for implementing I-T-type parallel logic operations is shown. This coherent OPC correlator was first proposed and demonstrated by White and Yariv[8] as a means to perform various coherent analog image convolution and correlation operations. In addition to a NLM cell, three equal focal length Fourier transform lenses are also employed. For the 2-D optical signals, E_A, E_D, and E_C in the front focal planes of three lenses, the phase-conjugated output is

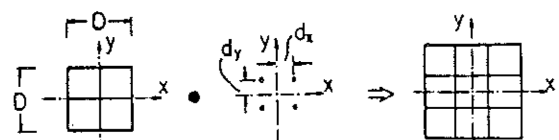


Fig. 3. Correlation of the overlapped inputs with four shifted δ-functions: D, width of coded input variable mask; d_{x_i} and d_{y_i}, displacements of the ith δ-function; (left) overlapped inputs containing four possible illuminated areas (see the left side of Table I); (middle) four shifted δ-functions; (right) the correlation result containing nine possible illuminated areas.

$$E_O \propto \chi^{(3)} E_A \circledast E_D \star E_C, \qquad (2)$$

where $\circledast$ and $\star$ denote correlation and convolution operations, respectively. To obtain the required multiplication operation for the I-T-type parallel OPC logic, the two logic input masks T_A and T_B are superimposed and placed on the E_A beam. In analogy to the I–T LED source array, a corresponding source mask T_C is inserted into the path of the E_C beam with four transparent dots representing four displaced Dirac δ-functions. Since no additional convolution is required, the E_D beam mask has a single on-axis dot representing a central δ-function. To obtain the correct correlation function, the E_C beam δ-function displacements d_{x_i} and d_{y_i}, where i = 1, 2, 3, and 4, must be chosen as

$$|d_{x_i}| = |d_{y_i}| = D/4, \quad (3)$$

where D is the input pixel size. Since the convolution of a function with a δ-function shifts that function after the OPC correlation/convolution operation, the needed I–T-type parallel OPC logic is obtained. To insure the correct correlation/convolution result, the NLM cell should be make thin enough to enclose only the optical Fourier spectra of the three interacting beams.[8–9] For clarity, in Fig. 3, the 2-D correlation of a square and four properly displaced δ-functions is illustrated. The leftmost box contains four subsquares, each of which represents a possible transparent area. When all four middle box δ-functions are on, the correlation result, shown in the rightmost box, contains nine possible illuminated areas. With this method, using sixteen possible on/off combinations of the four δ-functions, the sixteen two-variable binary logic operations can be performed. In the I–T method, because the input and output areas are not identical, in general, it is difficult to cascade two or more of these processors. For this reason, a conventional (black/white encoded) I–T OSC method is classified as single-instruction multiple-data (SIMD) processing.[4] To perform parallel MIMD operations, another encoding scheme, such as the use of polarization encoding,[10] is needed. In polarization encoding, the two orthogonal linear polarizations are used as two binary states. The thus encoded logic inputs, after a particular OSC manipulation, can generate two sets of orthogonal output patterns representing two different logic operations.

To summarize: the use of a real-time OPC triple-product device to generate coherent optical parallel logic operations is described. A NLM can be used as a major interconnection device that connects logic inputs to different output ports where different logic operations can be performed. The use of both the Yatagai and I–T-type parallel OPC logic implementation schemes is discussed. When both input signals are generated in real time, i.e., by two spatial light modulators, fast real-time parallel logic processing of 2-D data can be performed.

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