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AN AND OPERATION-BASED OPTICAL SYMBOLIC SUBSTITUTION PATTERN RECOGNIZER

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A new optical binary pixel pattern recognizer for optical symbolic substitution (OSS) digital computation is proposed. Using optical spatial shift and optical phase-conjugate AND operations, input symbolic pattern recognition can be performed. Some initial experimental results obtained with picosecond laser pulses are presented.

1. Introduction

Optics offers both the speed and parallelism required for digital signal processing and computation. Two promising parallel optical computation schemes are a parallel theta-modulation-based logic system suggested by Bartelt, Lohmann and Sicre [1] and optical shadow casting logic processors proposed by Ichioka and Tanida [2], and Yatagai [3]. To generate a complete set of two-variable boolean logic operations, there are other possible optical parallel structures [4–7]. Most recently, Brenner, Huang, and Streibl [8] proposed an optical symbolic substitution (OSS) computation scheme. With an OSS scheme instead of decomposing the computation into stages of boolean logic operations that use multiple inputs to generate a single output, both multiple spatial inputs and their relative locations are utilized to generate, in parallel, multiple spatial outputs.

The OSS method can be decomposed into a pattern recognition and scription step [8]. In its operation, pattern recognition (searching for the dark pixel locations) consists of possible input multiple spatial shifts, a collinear superposition (an OR), a threshold NOR, and a masking (an AND) operations. In this approach, for the shift and superposition operation, an interferometer is employed, while for the NOR operations, a matrix of parallel nonlinear optical threshold NOR gates is also used. From the DeMorgan's theorem, however,

$$\overline{(A+B+C\cdots+X+Y+Z)}=\bar{A}\,\bar{B}\,\bar{C}\cdots\bar{X}\,\bar{Y}\,\bar{Z} \qquad (1)$$

a multiple-input NOR gate can be synthesized with INVERTERs and AND gates [8,9]. For INVERSION, instead of searching for the dark, the white (transparent) pixels are recognized. Compared to a threshold NOR, an optical threshold AND-based approach has the advantage that it is easier to implement optically. However, in terms of signal-to-noise ratio, an optical threshold-AND gate may introduce an additional recognition error. When an N pixel pattern is to be recognized using an optical threshold AND gate, an output of one will be achieved only when the detected total intensity (NI_0, where I_0 is a single pixel intensity) is above a threshold. Thus, with this type of gate, one must distinguish between levels $(N-1)I_0$ and NI_0. As N increases, its noise immunity decreases. For this reason, a threshold NOR logic-based approach possesses a larger signal-to-noise ratio than its threshold AND-based counterpart [8]. For the pattern scription step, the previously recognized pixel pattern is used in another device where only spatial shift operations are performed.

In this letter, a new OSS pattern recognizer that employs a multiple-input boolean AND element is described and demonstrated. To recognize a multiple-white-pixel pattern, in addition to multiple spatial shifts, only AND operations are used. To prevent noise accumulation caused by a threshold-based approach, an optical phase-conjugate (OPC) mul-

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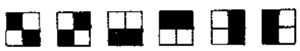
Table 1
Fourteen possible four-pixel optical symbolic patterns to be recognized. According to the number of transparent pixels, these patterns can further be classified into three groups. To recognize a N ($N=1,2,3$) transparent-pixel pattern, $N-1$ relative spatial shifts and a $N+1$ input AND gate is needed.

types	input patterns	No. of shifts	No. of inputs for AND
A		0	2
B		1	3
C		2	4

tiple-input boolean AND element is employed [7,10–11]. The advantages of using an OPC-based symbolic recognition scheme are discussed. Some preliminary experimental results using picosecond laser pulses are presented.

2. An AND-based symbolic pattern recognition

For an OSS operation, the first step is a symbolic pattern recognition. The input is a 2-D rectangular pattern array that contains several elemental light pixel patterns (the elemental patterns). For the purpose of this discussion, let the elemental pattern consist of a square of four-pixels. When the modulation is a transparent/opaque code, this elemental pattern can form sixteen different pixel combinations. Excluding the two trivial patterns (either all transparent or opaque) that can be recognized by other methods, in table 1, the remaining fourteen combinations are listed. These patterns can be classified into three groups: A, B and C. Since for the recognition of the four group-A patterns only an optical masking operation on these patterns is needed, no further discussion is presented.

To recognize the six group-B patterns, shift operations must be performed. As an example, consider the input pattern shown in fig. 1. The input image contains four four-pixel elemental patterns where one of them that contains two transparent main-diagonal pixels is to be searched. To recognize this four-pixel elemental-pattern, first, the image is replicated into two parts which are then either spatially shifted up or to the left by one unit, respectively. Together with

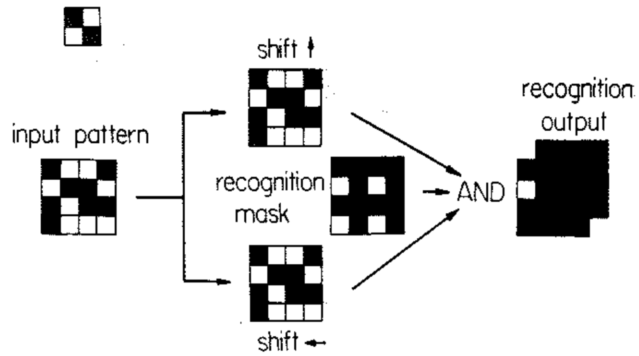


Fig. 1. Example of a four-pixel type-B pattern recognition. To locate the search pattern, two copies of the spatially shifted input are directed, together with a recognition mask, to a three-input parallel AND device.

a recognition mask that consists of four transparent pixels at the four elemental pattern's lower left-hand corners, the shifted images are next directed to a three-input 2-D parallel AND gate. In this case, its output indicates that the search pattern resides at the upper-right input image location. The three-input 2D AND operation can also be viewed as two cascaded two-input AND operations, i.e. an AND between the two shifted inputs, and a second AND between the first AND output and the recognition mask. In particular, the two two-input AND operations may help to discriminate against both intra- and inter-elemental-pattern noises. For other type-B inputs (see table 1), differential spatial shifts and recognition mask are used. When one of the two replicated inputs is stationary, only a single spatial shift, a shift that allows the two transparent pixels to overlap, is sufficient. For example, in fig. 1, by fixing the lower image position, only the upper image needs to be shifted in the upper right direction to a position where the two intra-elemental-pattern transparent pixels overlap. In general, to recognize a two-transparent-pixel pattern, a single relative shift and a three-input AND operation are required.

Similarly, for the group-C patterns, to discriminate against the intra-elemental-pattern noises, three copies of an input image with two relative shifts and a three-input AND element are needed. To discriminate against inter-elemental-pattern noises, an additional masking (AND) operation is used. As an example, in fig. 2, a type-C pattern recognition is

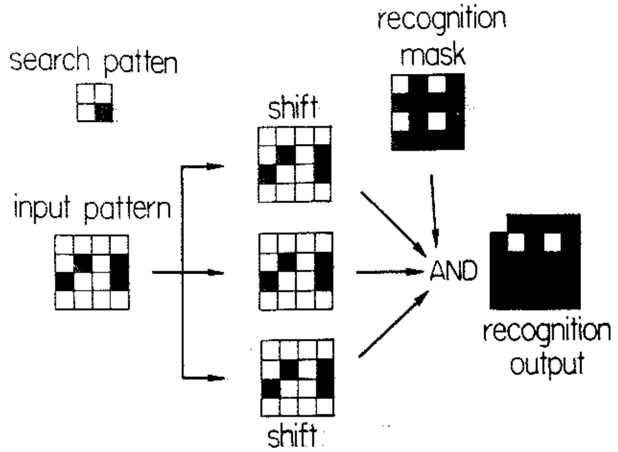


Fig. 2. Example of a four-pixel type-C pattern recognition. To locate the search pattern, three copies of the spatially shifted input are directed, together with a recognition mask, to a four-input parallel AND device.

shown. The input image contains two elemental search patterns. Here, either a single four-input or three two-input parallel AND elements needs to be employed. In general, to search for a N-transparent-pixel elemental pattern, $N-1$ pattern spatial shifts and a N-input parallel AND element must be used.

3. Optical implementations

In this section, the use of an OPC effect for a boolean multiple-input AND-based OSS pattern recognizer is described. In an OPC material, two counterpropagating optical beams and a third (coming from an arbitrary direction) arrive at a third order optical nonlinear $\chi^{(3)}$ material. When the phase matching condition is satisfied, in a backward (with respect to the third beam) propagation direction, a fourth, the so-called optical phase-conjugate (OPC) beam, is generated [10]. Using this OPC beam generation property, various analog and digital signal processing and computation applications have been proposed [7,10–11].

The OPC device can be considered as a three-input boolean logic AND element. In fig. 3(a), an OPC-based AND device is shown. A collimated type-B input image beam is divided, using a beamsplitter, intwo two copies. Directed by two plane mirrors, the two beams counterpropagate, with a relative spatial

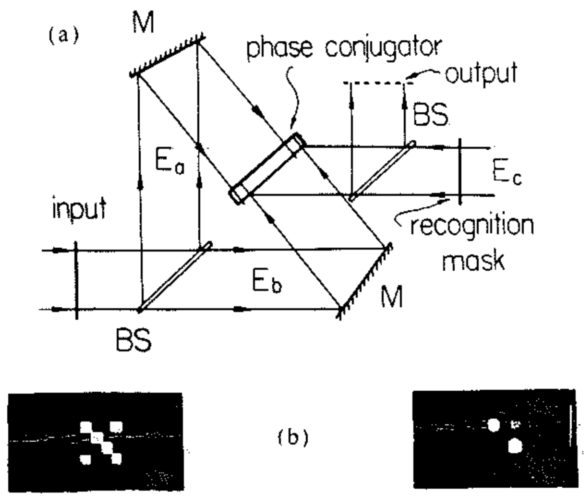


Fig. 3. (a) A schematic ultrafast OPC-based symbolic pattern recognition device. (b) Experimental result obtained with a 32 ps Nd^{3+} : YAG laser source and a 2 mm thick CS_2 cell. The input pattern that consists of four elemental-patterns is shown on the left-hand side where the elemental-pattern to be searched contains two main-diagonal transparent light cells. The recognized output pattern is shown on the right-hand side.

shift, to an OPC material. A third beam, containing the recognition mask, is also directed to the χ^3 material. The generated OPC signal counterpropagates with respect to the third beam. Finally, using a second beamsplitter, this signal is directed to the system output. With a slight modification, the OPC device can also be configured as a four-input, an element called for the type-C pattern recognition, AND element. In this case, all the three OPC input ports are used to carry spatially shifted input images. At the output port, the recognition mask is placed.

Using a polarization encoding method, it is also possible to collinearly combine the third beam with one of the counterpropagating inputs [10] (see fig. 4 for the geometry). Assume that the two counterpropagating inputs are linearly polarized. With a polarizing beamsplitting cube, the third input beam that is orthogonally polarized is also collinearly guided, with one of the counterpropagating inputs, to the nonlinear material. In this case, the polarization of the OPC output is identical to the third input polarization direction and it can easily be separated by the polarizing beamsplitter.

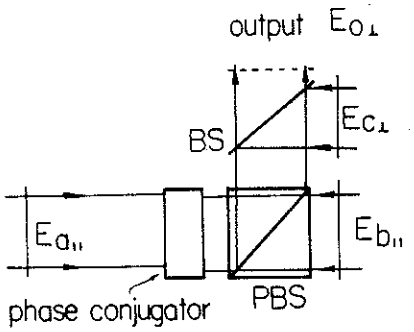


Fig. 4. An alternative OPC-based symbolic pattern recognizer. With orthogonal polarizations, input E_b and $E_{c\perp}$ are collinearly directed into the OPC material.

4. Experiment

To verify the operation of the OPC-OSS pattern recognizer, using a QUANTEL modelocked Nd^{3+} : YAG laser that generates 32-ps optical pulses, an experiment was performed. A 2× telescope was employed to expand the spatial profile to an area of 2 cm^2 out of which a small portion (about 1 cm^2) was used. For a larger aperture OPC pixel pattern recognition, before beam expansion, the source needs to be spatially filtered. In the experiment (see fig. 3(a) for the geometry), the sixteen-pixel input image contains four four-pixel type-B elemental patterns. The search pattern was a main-diagonal transparent pixel elemental pattern. With an appropriate spatial shift, the two beams (A and B) containing two shifted copies of the input mask were directed from the opposite directions to a 2 mm thick CS_2 cell. The recognition mask used in the probe beam (C) was angularly shifted by 5° from one of the counterpropagating beams. As illustrated in fig. 3(b), the picosecond OPC output signals shows that the expected search pattern was located at the input image uper-left and lower-right hand corners. The residue at the upper-right corner is the stray light noise. Using a threshold detector, this stray light noise can be filtered.

5. Discussion

This new OPC-based symbolic recognition scheme has the following advantages over the other schemes [8,9]:

(1) Instead of performing, as required by the scheme of ref. [8], three different (an image superposition equivalent to a logic OR, a threshold NOR and a masking equivalent to an AND) logic operations, here, only a single logic element, a multiple-input optical AND gate, is employed.

(2) The OPC-based scheme allows ultrafast processing. Using materials such as semiconductor-doped glasses or nonlinear polymers pico- or sub-picosecond OPC switching response times have been observed [12,13]. When the input binary pixel pattern is also generated by an ultrafast 2D modulation scheme such as from a parallel bistable etalon array [14] an ultrafast OSS pattern recognition can be performed.

(3) The OPC-based approach reduces the cumulative error that occurs with a threshold-based AND gate. This is true because the generation of an OPC-AND output is based on the input phase-matching condition that does not, to the first order, depend on the input intensity levels.

(4) The OPC-based approach also reduces the interference errors that occur in a collinear input pattern superposition geometry. With the refs. [8,9] schemes, it is important to perform a large aperture nearly perfect image superposition. Otherwise, any disturbance that changes input wavefront by a fraction of a wavelength will produce a slowly changing interference pattern leading to recognition errors. This is not the case with the OPC AND-based device since the off-axis angular inputs produce much higher density interference fringes. The averaged pixel intensity of the high density fringes can reduce the decision error.

(5) The OPC outputs are potentially cascadable. With a material, e.g. a multiple-quantum-well semiconductor, that exhibits a large nonlinearity and with an increased beam interaction region, e.g. a collinearly combined polarization-encoded OPC geometry (see fig. 4), an amplified OPC output can be obtained. The OPC amplification has been experimentally observed in CS_2 [10]. Thus, multiple-stages of OSS operation are possible.

One of the problems with the OPC-based scheme is that to recognize a N-transparent-input (where N is larger than three) pattern, a number of cascading AND stages are needed. This sequential operation does decrease the recognition speed. One way to minimize this problem is to use a tree-type (in $\log_3 N$ steps) logic decomposition structure. Another problem with the OPC-based scheme is that the OPC off-axis input is scaled causing a vignetted output. The polarization-encoded counterpropagating OPC geometry (see fig. 4) can eliminate this problem.

6. Summary

A new OPC binary pixel pattern recognizer for OSS has been proposed and demonstrated. Using a number of spatial shift and AND operations, a given optical pixel pattern can be recognized. For an optical implementation, mirrors and beamsplitters were used to obtain the required spatial shifts while an OPC-based device was used for the logic AND operation. Using an OPC-based scheme, ultrafast symbolic pattern recognition was experimentally demonstrated.

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References

[1] H. Bartelt, A.W. Lohmann and E.E. Sicre, J. Opt. Soc. Am. A1, (1984) 944.
[2] Y. Ichioka and J. Tanida, Proc. IEEE 72 (1984) 787.
[3] T. Yatagai, Optics Lett. 11 (1986) 260.
[4] M.T. Fatehi, K.C. Wasmundt and S.A. Collins, Jr., Appl. Optics 20 (1981) 2250.
[5] G. Eichmann, Y. Li and R.R. Alfano, Opt. Eng. 25 (1986) 91.
[6] T. Minemoto, S. Numata and K. Miyamoto, Appl. Optics 25 (1986) 948.
[7] G. Eichmann, Y. Li and R.R. Alfano, Appl. Optics 26 (1987) 196.
[8] K.H. Brenner, A. Huang and N. Streibl, Appl. Optics 25 (1986) 3054.
[9] M.T. Tsao, L. Wang, R. Jin, R.W. Sprague, G. Gigioli, H.-M. Kulcke, Y.D. Li, H.M. Chou, H.M. Gibbs and N. Peyghambarian, Opt. Eng. 27 (1987) 41.
[10] A. Yariv and P. Yeh, Optical waves in crystals (John Wiley and Sons, New York, 1984).
[11] T.R. O'Meara, D.M. Pepper and J.O. White, in: Optical phase conjugation, ed. R.A. Fisher (Academic Press, New York, 1983) p. 537, ch. 14.
[12] G.M. Carter, J.V. Hryniewicz, M.K. Thakur, Y.J. Chem and S.E. Meyler, Appl. Phys. Lett. 49 (1986) 998.
[13] P.P. Ho, N.L. Yang, T. Jimbo, Q.Z. Wang and R.R. Alfano, Ultrafast resonant optical Kerr effect in 4BCMUPDA, to appear in J. Opt. Soc. Am. B.
[14] T. Venkatesan, B. Wilkens, Y.H. Lee, M. Marren, G. Olbright, H.M. Gibbs, N. Peyghambarian, J.S. Smith and A. Yariv, Appl. Phys. Lett. 48 (1986) 145.