

Digital polarization-encoding technique for optical logic operations

Roberto Torroba, Rodrigo Henao,* and Claudia Carletti

Centro de Investigaciones Opticas, Casilla de Correo 124, La Plata, Argentina 1900

Received July 22, 1996

We implement optical logic operations, using a polarization-encoding architecture based on digital speckle pattern interferometry (DSPI). The method is based on the intensity dependence of DSPI on the rotation of the polarization direction in the paths of the interferometer between acquisition of frames. The 16 two-input logic operations can be achieved and stored in a host computer. This scheme also offers the possibility of creating dynamic logic gates. © 1996 Optical Society of America

In recent years, interest in the design of optical processors has constantly grown. Various methods have been proposed for implementing logic operations. Early versions were based on spatial filtering,^{1,2} where the logic gates were characterized by either grating structures or scattering structures. Modern approaches also exploited the use of laser-excited gratings in dye-doped solids.³ Successful implementations were based on the photorefractive effect, which was extensively studied in connection with optical computing.⁴ Photorefractive media were used to encode, transmit, and process information concerning logic operations under different architectures. Some of these techniques used, for example, phase-matched diffraction and holographic interference⁵ and multiwavelength encoding and processing.⁶ Polarization-encoded optical logic by use of photoinduced gratings in photorefractive crystals⁷ is particularly interesting, as such a scheme offers the possibility of creating dynamic logic gates. Including multiwavelength operations in this scheme offers the advantage of spectral parallelism in information processing.⁸

In the last context, the authors' preferences are oriented to make use of the representation of the logic states produced by two orthogonal states of linearly polarized light. Advantages of this approach are that no energy is lost, it is better suited for cascading operations, it requires no filtering or transformations, and it provides not only the result but also the negation of the result. Also, the requirements of intensity equalization and critical alignment are eliminated. Our objective is to use a digital approach based on the polarization-encoding concept as a means to simplify the truth table architectures. In this Letter we propose and demonstrate the implementation of polarization-encoded optical logic in a digital speckle pattern interferometer (DSPI) scheme. The DSPI scheme is a technique widely used in connection with metrological applications that is based on the digital correlation of speckle patterns.⁹⁻¹¹ The basic configuration that we use is shown in Fig. 1.¹² The laser beam is divided in two by a beam splitter, and then each beam is expanded. The input objects, A and B, are made such that they introduce a local change in the polarization direction in each beam. The polarization-modulated beams are

brought together to illuminate the surface. This is equivalent to obtaining two different speckle patterns from the same surface, one that serves as a reference wave and the other as an object wave. The resulting speckle pattern is recorded by a CCD camera and then processed with a host computer. The method relies on the speckle correlation concept, in which the correlation operation is performed by subtraction.

The technique combines holographic and speckle interferometry with an in-line reference beam and an image-plane hologram setup, following the methods of double-exposure holography. For comparison, a stored reference frame is continually subtracted from the incoming data. In the standard DSPI procedure, any optical path difference produced by a screen deformation introduces a phase change in the resulting speckle pattern of the actual frame. As a result, speckle correlation fringes are displayed on a TV monitor almost in real time, with the same interpretation as for those fringes obtained by holographic interferometry.

The visibility of such fringes depends on several parameters. Assuming linearly polarized laser light, we

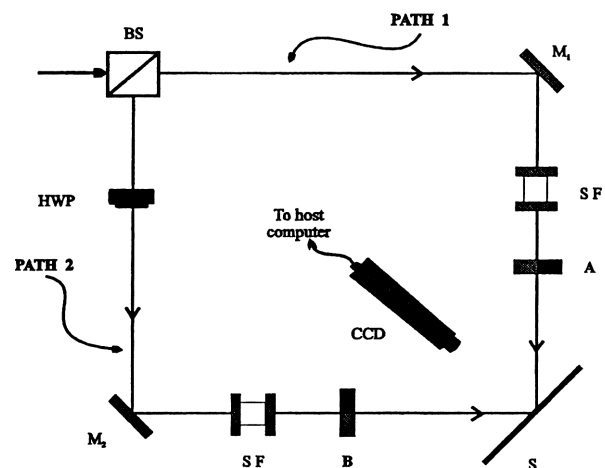


Fig. 1. DSPI setup: BS, beam splitter; M_1 , M_2 , mirrors; HWP, polarization rotator; SF's, beam expanders; A, B, input objects; S, reference diffusing surface; CCD, charge-coupled device camera.

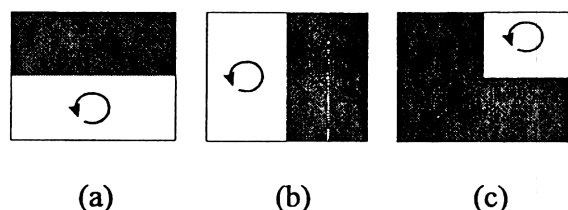


Fig. 2. Half-wave plate cell arrays in the input objects. (a), (b) Two-input objects. (c) Cell placed in one path of the interferometer. The curved arrows represent the sense of rotation induced by the half-wave plate.

note that, if a rotation is induced in the polarization direction in one path of the interferometer, a decrease in the fringe visibility can be observed.¹³ This indicates that the DSPI is polarization sensitive. The mechanism by which the polarization changes are stored in the DSPI has already been studied.¹⁴

If we denote the intensity distribution in the TV monitor that arises from the operation of a pixel-to-

pixel subtraction by $I(x, y)$ and assume that there are no phase disturbances between the reference frame and the actual one, then

$$I(x, y) = 4|A|^2 \sin^2 \Delta\theta \cos \varphi(x, y), \quad (1)$$

where A is the complex amplitude, which is assumed to be constant and equal in both paths, $\varphi(x, y)$ represents the phase of the resulting speckle pattern, and $\Delta\theta$ is the variation of the angle formed by the polarization direction in the stored reference frame with respect to the actual frames. When the directions coincide in both the reference and the actual frames, that is, $\Delta\theta = 0^\circ$ or $\Delta\theta = 180^\circ$, the TV screen is black; otherwise, if $\Delta\theta = 90^\circ$ or $\Delta\theta = 270^\circ$, the screen is white with a speckled background. Thus, after using a digital decoding procedure, we turn the polarization encoding into an intensity display on the TV monitor, which assigns a different intensity level to each recorded polarization rotation according to Eq. (1). The DSPI offers a

Operation	Path 1	Path 2	Experimental Result
0	Without Change	Without Change	
1	Polarization direction rotated 90°	Without Change	
A	Object A	Without Change	
B	Without Change	Object B	
\bar{A}	Object A rotated 180°	Without Change	
\bar{B}	Without Change	Object B rotated 180°	
A OR B	Object A	Object B and Object C rotated 180°	
\bar{A} OR B	Object A	Object B rotated 180° and Object C rotated 270°	
A OR \bar{B}	Object A	Object B rotated 180° and Object C rotated 90°	
A AND B	Object A	Object B rotated 180° and Object C	
\bar{A} AND B	Object A	Object B and Object C rotated 90°	
A AND \bar{B}	Object A	Object B and Object C rotated 270°	
A NAND B	Object A	Object B and Object C	
A EQV B	Object A	Object B rotated 180°	
A XOR B	Object A	Object B	

Fig. 3. Scheme showing how to perform all 16 logical operations and the corresponding experimental results.

means of easily implementing dynamic logic gates. The encoding concept is explained as follows: The two-input objects are array cells made of half-wave plates, as shown in Figs. 2(a) and 2(b). The arrows indicate the direction in which the half-wave plate switches the input direction of the linearly polarized light that is used as illumination source. The shaded areas indicate that no half-wave plate is present. A third array cell, displayed in Fig. 2(c), is placed in one path of the interferometer. This array is used to break the parity generated by rotation combinations that repeat some output results. In all cases, the reference frame is first stored without the object. We obtain the logical level 0 simply by not altering the setup. The TV monitor is black in this case. In the following, all rotations are clockwise. Level 1 is represented by a 90° rotation of the polarization direction in one path of the setup, which is accomplished by the polarization rotator. In this case the monitor screen is white. We display both input A and input B by inserting each separately into any of the interferometer paths. We obtain the negations of input A (\bar{A}) and input B (\bar{B}) by a 180° rotation of their original positions. The remaining operations are presented by examples. We accomplish operation A XOR B by simultaneously inserting the two input objects, A and B, in their original positions into separate paths of the interferometer. A EQV B is performed with the above configuration but with B rotated by 180° . We obtain the gate A NAND B by maintaining both inputs in their original positions on separate paths of the interferometer but inserting the third array behind B, with the half-wave plate in the upper-right position. By successively rotating this last array by 90° , we get \bar{A} AND B, A OR B, and A AND \bar{B} . Rotating B by 180° and rotating C by 0° , 90° , 180° , 270° , we get A AND B, A OR \bar{B} , A NOR B, and \bar{A} OR B, respectively. Details of the operations can be found in Fig. 3.

We have proposed and implemented a way to achieve all 16 two-input binary logic gates by a digital polarization-encoding scheme. The method relies on the intensity variations induced in a DSPI arrangement in which the polarization direction is altered with respect to the first reference frame acquired. The entire logic operation can be performed without alterations of the optical setup or auxiliary devices. The technique is independent of diffraction efficiencies and requires no transformations or filtering. The accuracy of the operations does not depend on critical alignment conditions. The intensity throughput is maximum throughout the whole process, as the half-wave plate rotator causes no loss of energy. In our case the signal-to-noise ratio is given in terms of the visibility of the resulting logic gate, which in all cases is approxi-

mately 0.6. The principal advantage over a standard electronic gate is the parallelism in processing that can be achieved by use of a more complex matrix as the input object, without the need for multiple operation units. Although we performed our experiments in a non-real-time realization, dynamic logic gates can be easily implemented. By use of a polarization-switchable device as an input object, such as a Pockels cell, near-real-time application can be achieved. The main limitation in the time between operations is set by the frame-acquisition rate of the video equipment.

This study was supported by grants from the Fundación Antorchas (Argentina), the Universidad Nacional de La Plata (Argentina), the Alexander von Humboldt Foundation (Germany), and the Third World Academy of Sciences (93-389 RG/PHYS/LA). R. Henao acknowledges the assistance of the Mutis Programme (Spain) and thanks C. Carletti of the fellowship Becario de la Comisión de Investigaciones Científicas (Argentina). The authors are also with the Facultad de Ingeniería, Universidad Nacional de La Plata (Argentina).

*Present address, Antioquia Investigaciones y Recursos en Tecnología, Apartado Aéreo 2073, Medellín, Colombia.

References

1. H. O. Bartelt, A. W. Lohmann, and E. E. Sicre, *J. Opt. Soc. Am. A* **1**, 944 (1984).
2. A. W. Lohmann and J. Weigelt, *Opt. Commun.* **52**, 255 (1984).
3. G. R. Kumar, B. P. Singh, K. D. Rac, and K. K. Sharma, *Opt. Lett.* **15**, 245 (1990).
4. P. Yeh, *Introduction to Photorefractive Nonlinear Optics* (Wiley, New York, 1993).
5. P. Yeh, S. Campbell, and S. Zhou, *Opt. Lett.* **18**, 903 (1993).
6. W. Wu, S. Campbell, S. Zhou, and P. Yeh, *Opt. Lett.* **19**, 646 (1994).
7. W. Wu, S. Campbell, S. Zhou, and P. Yeh, *Opt. Lett.* **18**, 1742 (1993).
8. W. Wu, S. Campbell, and P. Yeh, *Opt. Lett.* **20**, 79 (1995).
9. M. Lehman, J. Pomarico, and R. Torroba, *Opt. Eng.* **34**, 1148 (1995).
10. R. Henao, J. Pomarico, N. Russo, R. Torroba, and M. Trivi, *Opt. Eng.* **35**, 26 (1996).
11. R. Henao, H. Rabal, A. Tagliaferri, and R. Torroba, *Opt. Eng.* **35**, 63 (1996).
12. C. Joenathan and R. Torroba, *Opt. Lett.* **15**, 1159 (1990).
13. J. Pomarico, R. Torroba, and N. Bolognini, *Optik* **99**, 89 (1995).
14. R. Henao, A. Tagliaferri, and R. Torroba, *Opt. Commun.* **127**, 14 (1996).