Research on optical multistage butterfly interconnection and optoelectronic logic operations

DE-GUI SUN, NA-XIN WANG, LI-MING HE, MAI XU, GUO-DONG LIANG, JIE ZHENG

We briefly study butterfly interconnection construction and propose an experimental approach to implementing multistage butterfly interconnection networks by using a special interconnection grating with the reflection ladder structure and liquid crystal light valves (LCLVs), and implementing the optical butterfly interconnections and primary optical digital logic operations. With this foundation, we analyse and discuss the features of the approach by computer simulations. In terms of our theoretical analyses, we improve the ring-circuit approach, based on the reflection ladder structure gratings, into a more suitable form based on transmission gratings, and we substitute the LCLVs with optoelectronic switches. Finally we give the experimental results of both the transmission grating and optoelectronic switches.

KEYWORDS: butterfly interconnections, interconnection gratings, optoelectronic computing

Introduction

The research on optical interconnections and their applications in optical computing has been absorbing more and more attention because optics has many advantages, such as massive parallelism, free-space and high spatial bandwidth. Recently, a variety of optical interconnection technologies such as holography, optical gratings, and shadow-casting for symbolic substitution, etc have been developed and have obtained many successes[1,2].

The perfect shuffle, crossover, and butterfly interconnections have been used to implement optical computing systems[3,4]. According to our previous work[5,6], the butterfly interconnection network has many advantages over the other two networks in construction, and so is more suitable for the implementation of optical interconnection phase-gratings.

In this paper we propose an experimental approach to a ring-circuit to implement the multistage butterfly interconnection networks by using special interconnection gratings with reflection ladder structures and liquid crystal light valves (LCLVs), and obtain the experimental results of butterfly interconnection and the primary optical digital logic operations: that is, AND, OR and NOR. We then improve the optical experimental version into a more suitable form with transmission matched-gratings, and substitute the LCLVs with optoelectronic switches. We obtain the experimental results of the performances of transmission gratings and optoelectronic switches. Finally, we have a summary and conclusions.

The ring-circuit scheme and analyses

As we know, the butterfly network (as shown in Fig. 1) has two link lines, one is a straightforward line which is expressed with K^0_{i+1}, and the other is a butterfly interconnect line which is expressed with K^1_{i+1}; there are then relations (1) and (2)

$$K^0_{i+1} = K_i \qquad (K_i = 0, 1, \ldots, N-1) \tag{1}$$

$$K^1_{i+1} = \begin{cases} K_i + N/2^i, [(j-2)/2^{i+1} \leqslant K_{i+1} < jN/2^{i+1}] \\ K_i = N/2^i, [(j/2^{i+1} \leqslant K_{i+1} < (j+1)N/2^{i+1}] \end{cases}$$
$$(j = 1, 2, \ldots, 2^i) \tag{2}$$

D-GS and N-XW are in the Changchun Institute of Optics and Fine Mechanics, Academia Sinica, State Key Laboratory of Applied Optics, PO Box 1024 Changchun 130022, China. L-MH is at the Jilin University of Technology, Electronic Engineering Department, Changchun 130025, China. MX, G-DL and JZ are in the Changchun Institute of Physics, Changchun 130021, China.
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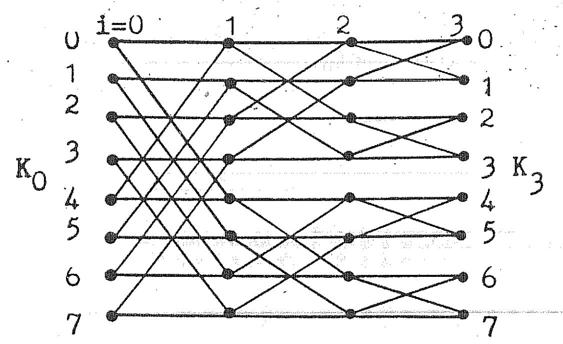


Fig. 1 The construction of multistage butterfly interconnect network: $N = 8$

where i is the number of the link stage ($i = 0, 1, \ldots, \log_2 N - 1$).

To implement the optical multistage butterfly interconnections the ring-circuit optical approach (as shown in Fig. 2) is used, where G_1 and G_2 are two interconnect gratings with the reflection ladder structure as shown in Fig. 3. While Mask 1 and Mask 2 are used to select the expected link lines, SP is the shift-plate which is used to shift the light beams to the next layer after circle operation, and the two

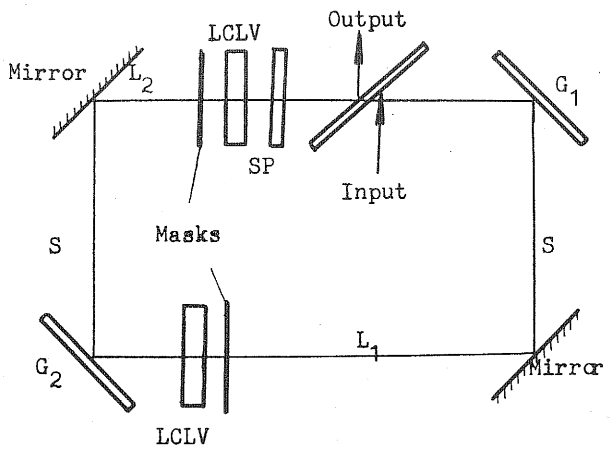


Fig. 2 The set-up for implementing the multistage butterfly interconnection network and parallel logic operations

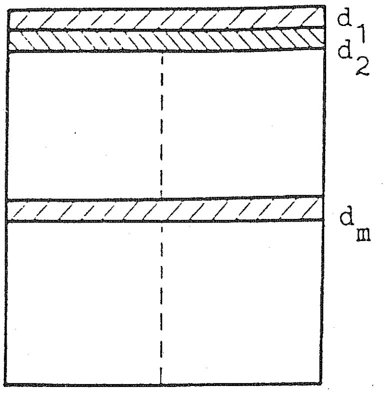


Fig. 3 The pattern of a ladder-grating array for the optical multistage butterfly interconnection network, where d_1 and d_m are the periods of the first and the mth grating strings, respectively

LCLVs, liquid crystal light valves, are optical logic devices. As shown in Fig. 3, the ladder grating array is composed of many grating strings with various periods. The d_i is the period of the ith grating string. If the first-order refractive angle of the mth grating string of G_1 is the same as that of G_2, we can obtain that the relative distances (as shown in Fig. 2) are required to meet relation (3)

$$L_1 + S = 2(S + L_2) \tag{3}$$

where L_1 is the distance between the mirrors and the LCLVs, and S is the distance between the gratings and mirrors.

With the optical experiment set-up, we obtain experiment results of the optical butterfly interconnection and the optical primary digital logic operations, as shown in Fig. 4, where (a) shows the input codes, (b) is the butterfly interconnection for the input codes, and (c), (d) and (e) are the AND, OR and NOR operations, respectively, for the input codes. We note that the experimental ring circuit, as in Fig. 2 for implementing the multistage butterfly interconnections, can induce the summed errors that are due to the refractive errors of the reflection gratings during designing and manufacturing, as well as the errors of the shift-plate, which depend on its distance from the output plane. As shown in Fig. 3, in terms of (2), d_m satisfies the following relation

$$d_m = 4^m d_1 \tag{4}$$

where d_1 and d_m are the periods of the first and the mth grating strings, respectively. If w is the distance

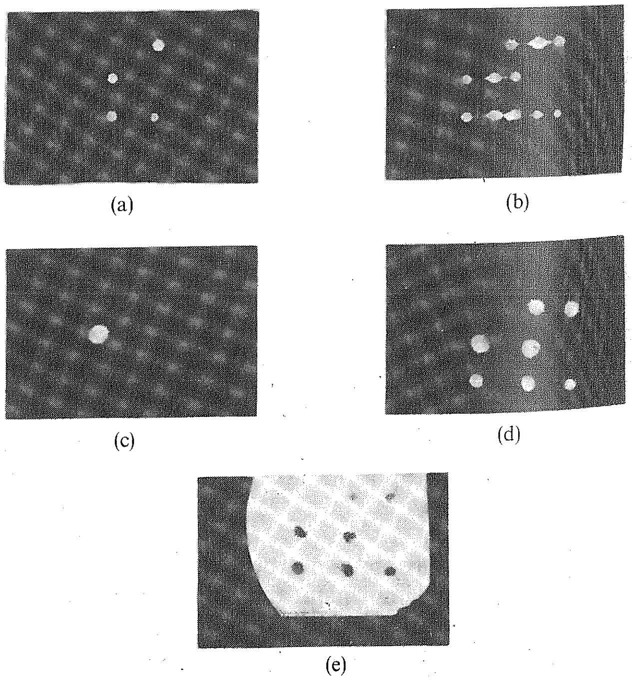

(a)
(b)
(c)
(d)
(e)

Fig. 4 The experimental results of the optical butterfly interconnection and primary optical digital logic operations: (a) original codes; (b) the results of one-stage butterfly interconnection; (c) the results of AND; (d) the results of OR; and (e) the results of NOR.

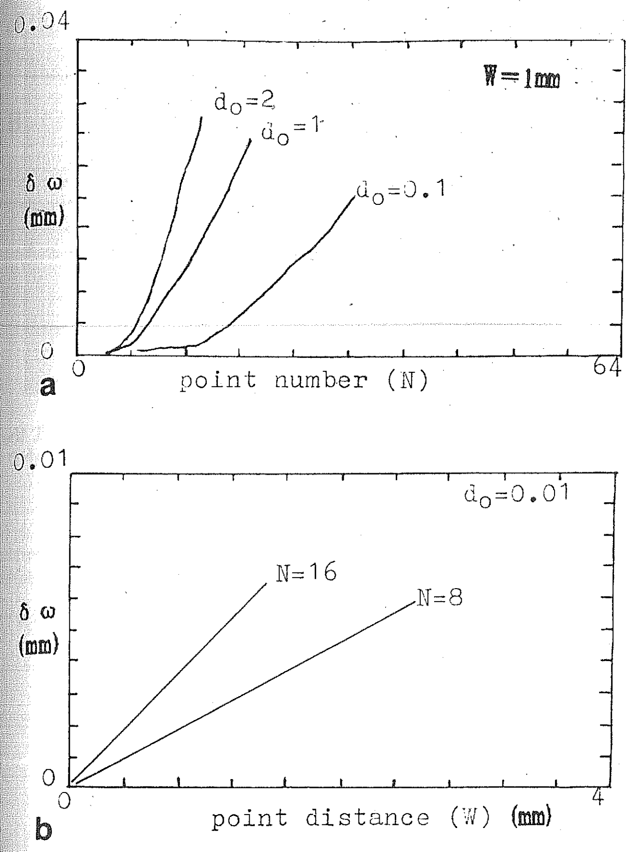


Fig. 5 The results of computer simulation for the limitations of a ring-circuit like Fig. 2: (a) the increase of the summed error with the light spot number (N); and (b) the increase of the summed error with distance between two adjacent spots (W)

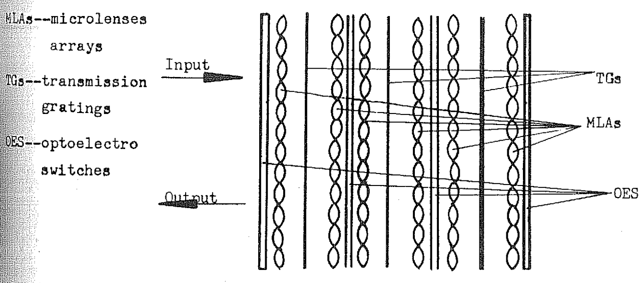


Fig. 6 The opto-electro approach with transmission gratings and optoelectronic switches

between two adjacent light spots, the error at the nth grating $\delta\omega_n$ then

$$\sin\theta_m = \lambda/(4^m d_1) \tag{5}$$

$$\delta\omega_n = \sum_{m=1}^{n/2} (L_1 \tan\theta_m + L_2 \tan\theta_m - NW/2^m) \tag{6}$$

where θ_m is the first-order refractive angle of the mth grating string.

Then we obtain the relation curves of the summed interconnection error of light spots, i.e. $\delta\omega_n$ with the number of light spots (N) and the distance of two adjacent light spots (W) as shown in Figs. 5 (a) and (b).

It can be noted that the summed interconnection error ($\delta\omega_n$) increases as both the number of light spots (N) and the distance of two adjacent light spots (W) increase. In addition, in this ring-circuit, because passive logic devices (LCLVs) are used, the power complement, and the experimental adjustment are very difficult and the system integration is not easy to implement. Therefore, this circuit scheme for implementing digital optical computing must be improved.

The optoelectronic transmission butterfly scheme

It can be noted that the interconnection error will sharply increase with both N and W. Consequently, this ring butterfly interconnection circuit, based on the reflection ladder gratings, is limited in its application to multistage interconnection in digital optical computing. In order to overcome this disadvantage, we improve our implementation approach to the form based on transmission gratings, as shown in Fig. 6, where OESes are optoelectronic switches and are used to substitute the original LCLVs. With this approach calculation accuracy can be greatly improved. In the latter implementation approach, there are two methods of arranging the transmission gratings, as shown in Figs 7(a) and (b), respectively. Relations (7) and (8)

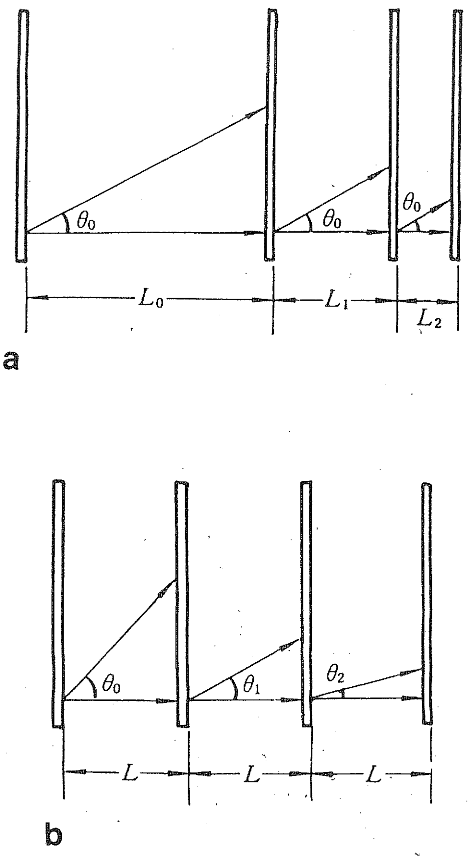
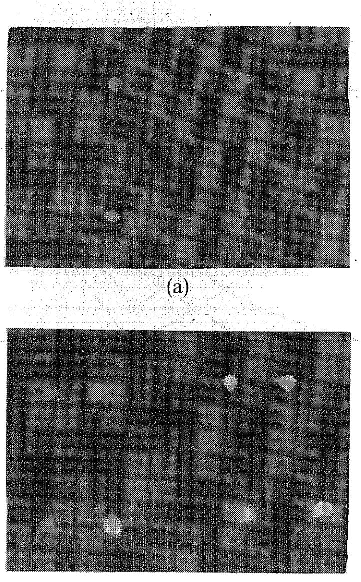


Fig. 7 The arrangements of transmission gratings for multistage butterfly networks. (a) Changing the distances L_i between two gratings; and (b) changing the periods of gratings d_i


(a)

(b)

Fig. 8 The diffraction experiments: (a) input signals; and (b) experimental results

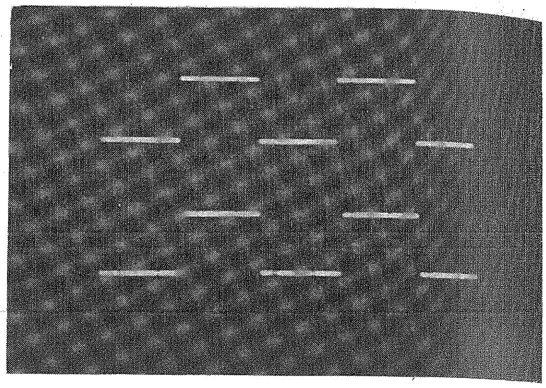


Fig. 10 The experiment result of logic performance of OES, the upper curve is the input signal; and the lower curve is the AND operation result of the two input signals

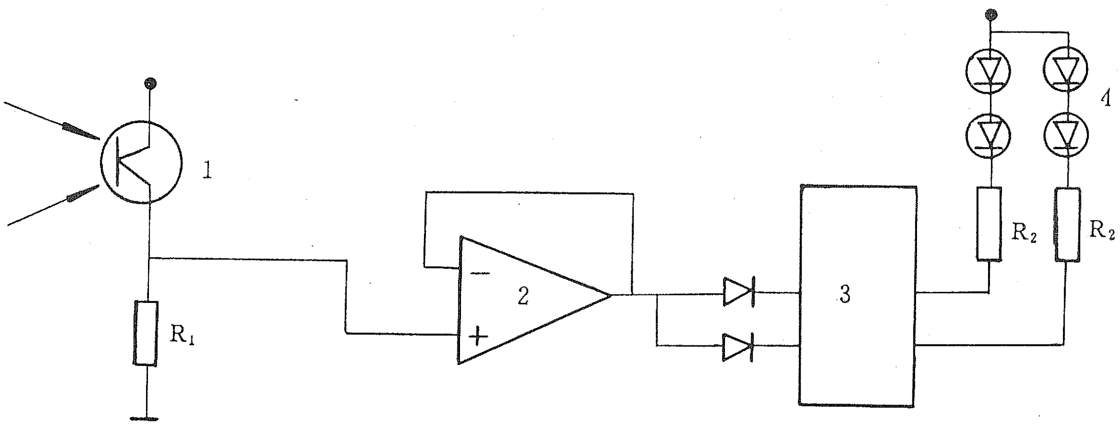


Fig. 9 OES circuit: (1) photo-sensitive diode; (2) modifier; (3) electronic gate device; and (4) LEDs

describe the two arrangement relations of Figs 7(a) and 7(b), respectively

$$L_i = \frac{NW}{2^{i+1}\tan\theta_0} \quad (7)$$

$$d_i = \frac{\lambda L}{WN/2^{i+1}} \quad (8)$$

where W indicates the distance between the two adjacent spots, and θ_0 indicates the diffraction angle. The diffraction experiment results of the transmission grating are shown in Fig. 8, where Fig. 8(a) shows the input signals and Fig. 8(b) the experimental results. The circuit is constituted by using photosensitive diodes, light-emitting diodes, electronic modifiers and their associated electronic devices, as shown in Fig. 9, so we obtain the experimental results of the logic performance of this optoelectronic switch, as shown in Fig. 10, where the upper wave curves are the input signals, and the lower curves are the experimental results of the AND operations. Of course, the logic performance of the OES is better than that of the LCLVs, and more fitted to power modification and experimental adjustment.

Summary and conclusions

We have studied the multistage butterfly interconnection network. First, we proposed a ring-circuit optical implementation scheme based on reflection gratings and LCLVs, and obtained the results of butterfly interconnection and primary digital logic operations: AND, OR and NOR. Secondly, we analysed the ring-circuit version with computer simulations and found its limitations in digital optical computing. Finally, in terms of the experiments and analyses, we improved the ring-circuit scheme, based on the reflection gratings and the LCLVs, to the more practical form with transmission gratings and optoelectronic switches, which can resolve the stability and integration, respectively, of this version in digital optical computing and provide the experimental results of the performances of transmission gratings and optoelectronic switches.

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