Polarization Multi-functional Image Switch for Optical Interconnection and Parallel Processing

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Abstract

An novel approach to parallel and high-speed data communication and data processing by optical technology is presented. A multi-functional image switch is designed based on polarization modulation. The device is constructed with a polarized beam splitter cube and four controllable phase modulators. A LC electro-optic modulator is used for obtaining zero and $\lambda/2$ phase retardation, and thus realizes conversion between p- and s-polarized signals. Sixteen functions in binary logic can be obtained by programming the four modulators. Significant features of the proposed device are its 2D image parallel processing ability and the diffraction-limited throughput. Applications to optical interconnection and parallel image processing are addressed. Parallel arithmetic algorithms are presented based on modified-signed digit representation.

1. Introduction

The potentials of optical technology for data communication and data processing are widely discussed. The two-dimensional parallelism and high interconnection density provided by free-space optics can be used to overcome the communication bottlenecks in electronic computing system and can extremely increase the computing ability. Achievements related to those optical technology are such as synthetic aperture radar signal processing, optical matched filtering, optical fiber communication, holographic display technologies, and laser disc memory technologies.

Recently, optical interconnection [1] is widely recognized to overcome the communication bottlenecks in computer, because optical transmission signals can be multiplexed in the time, space, and wave-length domains. Several models for optical interconnect have been studied. The optical cross bar interconnect, the mesh interconnect, the hypercube network, and the multistage interconnect network have been pursued in many recent research proposals. Usually, an optical interconnection network (OIN) is designed to connect N input ports to N output ports by using one or several node arrays connected by free-space channels, and each node has ON and OFF, or bypass and exchange statuses to guide optical signals [2]. The increasing the network size implies increasing the node array, the integrated intensity, the controlling complexity, and the cost. Especially in some cases such as visual image processing, where a serial images must be transmitted and processed with high speed, the present technique has arrived to close its theoretic limitation.

The motivation of this research is to realize high-speed and parallel data communication and data processing by exploring the spatial free domain. Continuous 2D image data switches instead of pixel-wise switches is discussed in this paper. Image parallel switch elements, data representation methods and arithmetic algorithms are proposed.

We firstly describe design of multi-functional image switch (MFIS), the operation principle and the evaluation characteristic of critical components, and then potential applications to image-channel interconnection and parallel arithmetic processing are presented.

2. Polarization Multi-functional Image Switch

2.1 Operation Principle

The operation mechanism of a polarization multi-functional image switch relies an a polarizing beam splitter cube (PBSC), four imaging lenses , and four electro-optic controllable phase modulation plates (PMP). The PBSC separates the s- and p-polarized components of an input beam signal, also it combines the s- and p-polarized components of two input beam signals as shown in Fig. 1. The imaging lenses form a confocal imaging between input planes and the output planes for realizing diffraction-limited resolution. A PMP has ON and OFF two statuses, and the ON status can act as a $\lambda/2$ phase retardation while the OFF status acts nothing. By

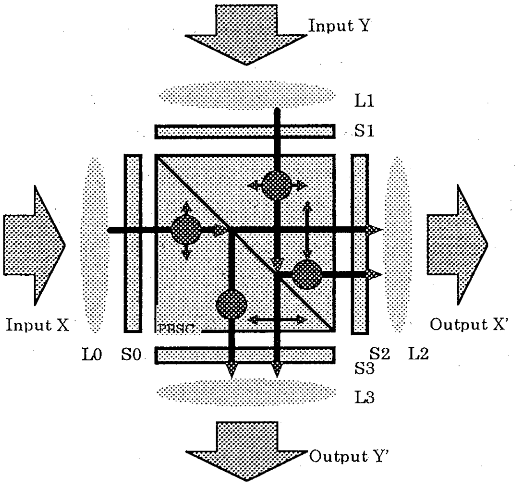


Fig. 1 Schematic configuration of multi-functional image switch.

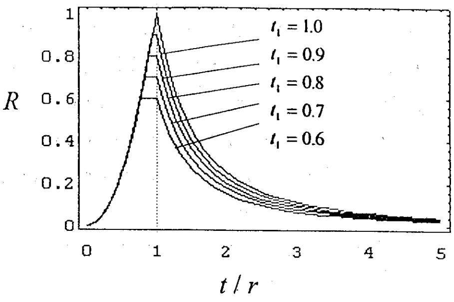


Fig. 2 Relationship between output contrast R and the ratio t_p / r_s at several parameters t_1.

setting the PMPs to ON or OFF status, the image at a input ports can be switched to one of two output ports. Sixteen switch operations can be realized by programming the four PMPs (Table 1). Generally, the output can be expressed as:

$$X'_P = \overline{S}_0\overline{S}_2X_P + S_0\overline{S}_2X_S + S_1S_2Y_P + \overline{S}_1S_2Y_S$$

$$X'_S = \overline{S}_0S_2X_P + S_0S_2X_S + S_1\overline{S}_2Y_P + \overline{S}_1\overline{S}_2Y_S$$

$$Y'_P = S_0S_3X_P + \overline{S}_0S_3X_S + \overline{S}_1\overline{S}_3Y_P + S_1\overline{S}_3Y_S$$

$$Y'_S = S_0\overline{S}_3X_P + \overline{S}_0\overline{S}_3X_S + \overline{S}_1S_3Y_P + S_1S_3Y_S$$

where Xs (Ys) and XP (Ys) and are p- and s- polarized beam signals, respectively. S_i denotes the status of ith PMP. Bypass and exchange operations are realized by programming the four PMPs to be OFF / ON status.

Table I Truth-table for a polarization-based multi-functional image switch.

S_0	S_1	S_2	S_3	X'_p	X'_s	Y'_p	Y'_s
0	0	0	0	X_p	Y_s	Y_p	X_s
1	0	0	0	$\underline{X_s}$	Y_s	Y_p	$\underline{X_p}$
0	1	0	0	X_p	$\underline{Y_p}$	$\underline{Y_s}$	X_s
1	1	0	0	$\underline{X_s}$	$\underline{Y_p}$	$\underline{Y_s}$	$\underline{X_p}$
0	0	1	0	$\underline{Y_s}$	$\underline{X_p}$	Y_p	X_s
1	0	1	0	$\underline{Y_s}$	X_s	Y_p	$\underline{X_p}$
0	1	1	0	Y_p	$\underline{X_p}$	$\underline{Y_s}$	X_s
1	1	1	0	Y_p	X_s	$\underline{Y_s}$	$\underline{X_p}$
0	0	0	1	X_p	Y_s	$\underline{X_s}$	$\underline{Y_p}$
1	0	0	1	$\underline{X_s}$	Y_s	X_p	$\underline{Y_p}$
0	1	0	1	X_p	$\underline{Y_p}$	$\underline{X_s}$	Y_s
1	1	0	1	$\underline{X_s}$	$\underline{Y_p}$	X_p	Y_s
0	0	1	1	$\underline{Y_s}$	$\underline{X_p}$	$\underline{X_s}$	$\underline{Y_p}$
1	0	1	1	$\underline{Y_s}$	X_s	X_p	$\underline{Y_p}$
0	1	1	1	Y_p	$\underline{X_p}$	$\underline{X_s}$	Y_s
1	1	1	1	Y_p	X_s	X_p	Y_s

2.2 Properties and Evaluation of Critical Components

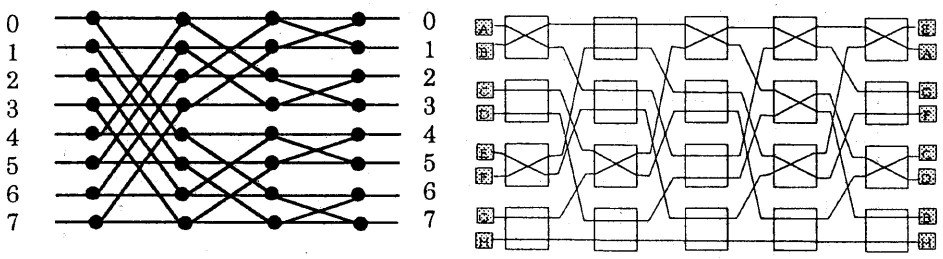
The performance of the MFIS strongly depends on the qualities of the PBSC, and the PMPs. The PBS's must efficiently separate and combine the s- and p-polarized components of the input beams. The transmittance t_p of p-polarized light must identical with the reflectance r_s of the s-polarized light, and reflectance r_p of the p-polarized beam and the transmittance t_s of the s-polarized beam must be zero. Fig.

2 shows the relationship between output contrast R and the ratio $\frac{t_p}{r_s}$, while t_1 is bright transmittance of a PMP. High-quality thin-film PBS's are commercially available in both the visible regions (400-700nm) and the near-infrared regions(620-1000nm). Typical extinction ratios exceed 1000:1 in a 300nm bandwidth around the central wavelength.

The electro-optic phase retarder is required for introducing an accuracy $\lambda / 2$ phase retardation to convert the s-polarized light to p-polarized, and vice versa. A liquid-crystal cell is usable because the phase retardation can be controlled by an applied voltage. A feedback circuit may be applied to obtain a desired phase retardation. For a LC tunable half-wave plate, the siwtch time is in the millisecond regime. Alternatively, switching time may be reduced to a few nanoseconds if a solid-state half-wave plate, such as a thin-film lead lanthanum zirconated titanate (PLZT) or a Pockels cell, is used. The trade-off is in the high voltage requirement for the solid-state switching devices. We utilized commercially available quartz waveplates in our firstly evaluation experiments.

3. Image-channel Interconnection Networks

Image-channel interconnection network can be constructed with the MFIS proposed. The configuration is similar with the conventional network constructed with pixel-wised switch devices. An conventional optical multistage interconnect network (as shown in Fig. 3a) can be characterized by pixel-wised 2×2 switches and optical paths that follow bit-wised signals.



(a) (b)

Fig. 3 (a) A typical multistage interconnection network with 2×2 pixel-wised switches, (b) An image-channel shuffle-exchange network for image transmission.

An image-channel interconnection is proposed in which each path is a light beam carrying two-dimensional optical encoded information, and the switch node is an image-parallel element. This image element switches all pixels of an image concurrently. Thus as shown in Fig. 3(b) an image-channel interconnection network provides data communication among serial images.

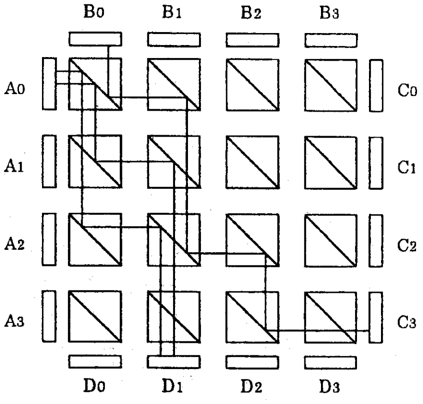


Fig. 4 An 8 × 8 redundant image-channel interconnection.

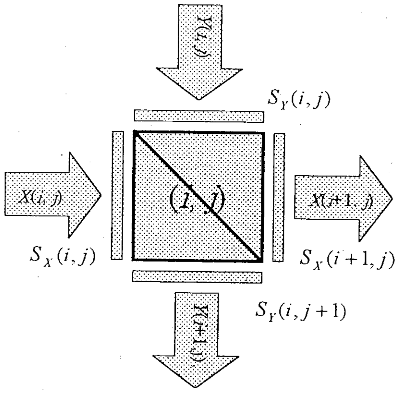


Fig. 5 Routing for a MFIS array.

The multiple switch characteristics of MFIS is employed to construct a novel redundant interconnection network. Figure 4 shows a redundant 8 × 8 image-channel interconnection network. Figure 5 shows how to routing the network. Input and output relationship of the (i, j) th MFIS in the network can be generally expressed as:

$$\begin{pmatrix} X(i+1,j) \\ Y(i,j+1) \end{pmatrix} = \begin{pmatrix} S_X(i+1,j)A_0S_X(i,j) & S_X(i+1,j)A_1S_Y(i,j) \\ S_Y(i,j+1)A_1S_X(i,j) & S_Y(i,j+1)A_0S_Y(i,j) \end{pmatrix} \begin{pmatrix} X(i,j) \\ Y(i,j) \end{pmatrix},$$

and

$$A_0 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \qquad A_1 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}.$$

4. Parallel Arithmetic Processing Algorithm

Alternative application of MFIS is parallel image arithmetic logic processing. We consider visual images are a set of 2D images and processing is done by the arithmetic logic operation among the images.

We have studied the parallel arithmetic algorithms for scaleable 2D data computing based on modified-signed digit (MSD) number system [4-6]. The MSD system uses three digits of 1, -1, and 0 to encode a number, and can realizes carry-free operations. The array addition can be expressed with 13 combinational logic functions, where only 1-bit binary addition and multiplication are involved. Figure 6 shows an optical circuit for implementing these logic formulae. The solid line denotes a collimated light beam. The symbols above lines indicate pattern information carried by the light beam. The architecture consists of more than 50 optical elements [6]. However, the configuration can be significantly simplified by using MFIS's.

5. Conclusion

We have presented several novel approaches to parallel and high-speed data communication and data processing by optical technology. The designed of a multi-functional image switch is described based on polarization modulation. The evaluation experiment is carried out by using commercial available quartz halfwave plates and polarizing beam splitter cube. The operation principle is simply, but, the performance is strongly depends on the accuracy control of the phase retardation and the transmittance and the reflectance of PBSC, and thus special design and custom fabricate is necessary. A potential application of the MFIS includes such as image-channel interconnection network and arithmetic logic unit for image-parallel processing.

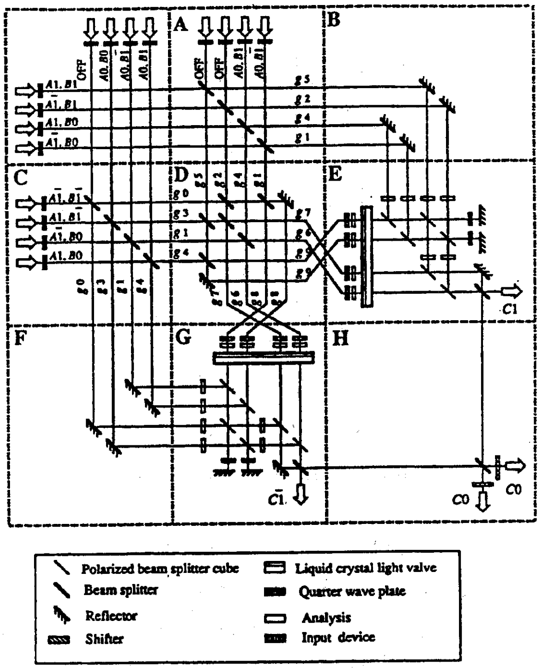


Fig. 6 Optical circuit of a MSD adder.

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