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Design of micro-optics array to realize two dimensional perfect shuffle transform

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ABSTRACT

Two-dimensional (2D) perfect shuffle transform (PST) plays an important role in optical communication and optical information processing due to very high space-bandwidth product (SBWP) and spatial degrees of freedom. The planar-array of micro-blazed grating has been proposed to realize 2D PST based on its interesting properties such as high diffraction efficiency, small size, high degree of integration, and easy to fabricate. 2D PST could be realized in free space through controling the etching direction and the period of micro-blazed grating, which results in signal beams can reach the desired spatial position. Unlike the conventional method depending on the operation of dividing, magnification, interlacing, and superimposing, this approach, which mainly relies on the diffractive properties of signal beams and the distribution of light intensity, presents a single diffractive element to perform 2D PST. Thus, this approach has the advantages of high energy efficiency, high feasibility, compact in structure, and easy to integrate. The theoretical analyses and the experimental results show that it should be helpful in optical interconnection network, especially, in PS omega network.

1. Introduction

With the development of the optical digital computer, optical interconnection techniques have become one of the most important fields, attracting more and more researchers because of its potential to implement massively parallel architectures [1–3].

There are three well-known types of interconnection networks: crossbar networks, bus networks, and multistage interconnections. Crossbar networks constructed from a single crossbar switch containing N^2 cross points are strictly nonblocking (i.e., any two channels can be connected without altering any existing connection), where N is the number of channels. However, the complexity and cost rise as $O(N^2)$. Bus networks have the simplest structures and are easy to build, but they suffer from a serious propagation delay (proportional to N) and contention problems. Multistage networks are a compromise between the two networks described above. For N channels, where $N=2^m$, the network delay is proportional to m, where m is an integer, whereas the cost and complexity is proportional to $N \times m$. Thus multistage networks have attracted great interest recently. A full access rearrangeable-nonblocking multistage interconnection network is composed of several stages of fixed link patterns combined with dynamic switch elements at each stage. Different architectures of multistage networks based on various link patterns such as the omega/shuffle-exchange network, the Baseline network, the Banyan network, and the crossover network, have been proposed [4,5]. It has been shown that all these networks are topologically equivalent.

The omega/shuffle-exchange network attracts the most attention because of its relatively regular and simple structure [6]. The link pattern of the omega network is

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based on PST [7–10]. In the PS the N channels (assuming that N is even) are divided into two halves; these two halves are then interleaved perfectly. At each stage, neighboring pairs of channels are connected through switch elements. As a consequence, a path between any two channels can be established when enough stages are proposed, and when the switch elements are properly controlled.

2. Related works

PS was first proposed in the parallel processor to implement parallel computing (such as the fast Fourier transform, polynomial evaluation, sorting, and matrix transposition) [11]. For any positive integer n, there exist two permutations of the set $Z_{2n}=\{0,\ldots,2^n-1\}$, called the shuffle and the shuffle-exchange, such that for any x, y in Z_{2n}, there is a permutation $\pi(x, y)$ of Z_{2n} mapping x onto y, such that $\pi(x, y)$ is the product of n permutations, each one of them being the shuffle or the shuffle-exchange. This result is optimal. One consequence is that one can construct a dynamic memory in which each word is connected to two other ones (by the shuffle and the shuffle-exchange), in such a way that the access time for a word is proportional to the logarithm in base 2 of the size of the memory. Here the shuffle is the $(2, 2^{n-1})$-shuffle, while the shuffle-exchange is the product of that shuffle with the exchange permutation interverting even and odd numbers in Z_{2n} (0 with 1, 2 with 3, etc.).

PS has been widely applied in optical communications, optical computing, and computer sciences. For example, certain parallel processing algorithms are conveniently executed on a PS based architecture. There is an *in-place* merging algorithm [12,13] which reduces the list merging problem to the problem of realizing the PS [14,15]. Sorting is one of the most fundamental problems in computer science. A new in-place, stable and shuffle-based merge algorithm is presented, which starts applying PS on two sorted arrays. Then, using the knowledge that odd and even indexed numbers are sorted among themselves, comparisons are made and then misplaced elements are relocated by applying successive inverse PS and swap operations on blocks [16]. An optical shuffle-exchange interconnection network based on Arrayed Waveguide Gratings (AWGs) was also designed [17]. It proposes implementations of the network suitable to be exploited in an optical backplane that interconnects line-cards of a high-performance switch or router. A procedure to design AWG interconnection stages with zero coherent crosstalk was presented, which applied the PS pattern to the building block of the shuffle-exchange. In addition, based on the Left Perfect Shuffle (LPS) optical communication network constructed by cascade multistage LPS interconnection, any arbitrary sequence of the input signals can be realized using looping algorithm [18]. Thus, it is a vital role to realize PS using optical methods and devices.

Free-space optics has the advantages of parallelism, low crosstalk, which comes from the use of imaging optical techniques, combined with regular space-variant manipulations (such as splitting and shifting of large arrays of processing elements). Hence, free-space optics appears ideal for implementation of the PS in applications with high data rates or many parallel channels like telecommunications and fine grained parallel processors. Until now, many investigators have been working on optical implementation of the PS, and several approaches have been proposed and demonstrated [19]. These approaches include the use of conventional optics such as lenses and prisms, as well as diffractive optics, which base on either imaging or interferometric techniques. To fully utilize the three-dimensional nature and the inherent parallelism of optics, one would like to perform optical 2D PS operations on a 2D input plane to produce a 2D output plane. We concentrate here on free-space techniques for performing this operation.

Optical 2D shuffles can be implemented by modifying existing methods for performing 1D PS [20]. The major drawback of this approach is that the resulting system becomes either complex or inefficient. Four simple lenses were used for 2D fold shuffle by Stirk and Sheng [21,22]. Sawchuk and Glaser [23] accomplished both 2D folded and 2D separable shuffles by a similar approach. In both of these implementations, four copies of the magnified and masked input plane are generated. By shifting and superimposing these four copies properly, the shuffled version of the input plane appears in the center as a result of the overlap from the four copies. In this method, no more than 25% light efficiency can be obtained because only one quadrant of each copy is retained in the output. Wang et al. [24] utilized only one copy of the magnified plane to perform the 2D shuffles. The magnified plane is considered to be composed of four equal size submatrices. Each submatrix is shifted and then stacked to produce the 2D shuffled version of the input plane. This method does not require extra copies of the magnified input plane; therefore, 100% light efficiency can be achieved in principle. However, its holographic experimental setup has the disadvantages of high cost, large element volume, and no flexibility. Moreover the experimental parameters must be further optimized to compensate for the severe diffraction effects in the experiment.

In this paper, we introduce a new method to perform 2D PS interconnection utilizing only one element (micro-blazed grating planar-array), which may be more feasible and more favorable than other approaches known so far. The characteristics of PS transform are described briefly in the next section, followed by the analysis of 1D PS transform using micro-blazed grating array in Section 4. Simultaneously, 2D folded PS and 2D separable shuffles could be realized by utilizing the planar-array of micro-blazed grating. The experimental results and the theoretical analysis (including diffractive efficiency and crosstalk) are presented in Section 5, followed by the briefly discussions in Section 6. Finally, a simple conclusion is outlined in Section 7.

3. The definition of PST

3.1. 1D-PST

The PST can be regarded as a one-to-one permutation of a group of N inputs. Specifically, it consists of dividing an input array into two halves and interlacing the elements of the two halves to form an output array. Mathematically,