Rearrangeable Nonblocking 8 × 8 Matrix Optical Switch Based on Silica Waveguide and Extended Banyan Network

Ying Zha, De-Gui Sun, Tie-Gen Liu, Ying Zhang, Xiaoqi Li, and Xiuhua Fu

***Abstract*—Based on the crossbar network and the Banyan network (BN), a new rearrangeable nonblocking structure of extended Banyan network (EBN) was proposed for implementing an 8 × 8 optical matrix switch. The interconnection characteristics of the rearrangeable nonblocking EBN were studied, and the diagram of the logic program for driving the operation of switching units was provided. A silica waveguide 8 × 8 matrix optical switch was designed and fabricated according to the calculated results. The silica waveguide propagation loss of 0.1 dB/cm and waveguide-fiber coupling loss of 0.5 dB/facet were measured. With the fabricated 8 × 8 matrix optical switch, the insertion loss of 4.6 dB, the crosstalk of −38 dB, the polarization-dependent loss of 0.4 dB, the averaged switching power of 1.6 W, and the switching time of 1 ms were achieved. A basic agreement between experimental results and theoretical calculated values was achieved.**

***Index Terms*—Extended Banyan network (EBN), matrix optical switch, rearrangeable nonblocking, silica waveguide.**

I. Introduction

PHOTONIC network systems, including optical add–drop multiplexing and optical cross-connect systems, have led to the need for larger-scale optical matrix switches [1]. These optical matrix switches typically include the microelectromechanical system switch [2]–[4], bubble switch [5], [6], and liquid crystal switch [7]. Silica-based planar lightwave circuit (PLC) technology, with the material thermooptic effect, shows a promising essence of application in fabricating large-scale optical matrix switches because of its many advantages such as no moving parts, low optical loss, excellent compatibility with mature semiconductor techniques, and low cost [8]. Nevertheless, the device size and insertion loss (IL) are two critical restrictive factors for silica-based PLC technology to become a widely acceptable technique of large-scale matrix switches. The crossbar network (CN), a typical strictly nonblocking network, needs many stages of switching units in series. Typically, when the number of optical switch ports is eight or more, the whole device layout will be too long to be fabricated on a silicon wafer, so the loop-type (curved) layouts must be used in the CN-based optical matrix switches. As a result, the more stages and the loop-type layout both result in the large optical loss. The Banyan network (BN) needs fewer stages and then a switch with a scale of 16 × 16 or more can be realized in a silicon wafer in linear style (without loop-type layout). Various nonblocking networks based on BN have been brought forward to optimize the device size and IL [9]–[11]. In this letter, we demonstrated a new rearrangeable nonblocking optical matrix switch based on the extended Banyan network (EBN) with its rearrangement routing a logic diagram of the driving program and excellent calculated and measured results.

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Y. Zha is with the Key Laboratory of Opto-Electronics Information and Technical Science of the Ministry of Education, School of Precision Instrument and Opto-Electronics Engineering, Tianjin University, Tianjin 300072, China, and also with the State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, JL 130033, China.

D.-G. Sun is with the State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, JL 130033, China, and also with the State Key Laboratory of Semiconductor Lasers, Changchun University of Science and Technology, Changchun, JL 130012, China (e-mail: deguisun_b@yahoo.com).

T.-G. Liu is with the Key Laboratory of Opto-Electronics Information and Technical Science of the Ministry of Education, School of Precision Instrument and Opto-Electronics Engineering, Tianjin University, Tianjin 300072, China.

Y. Zhang and X. Li are with the State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, JL 130033, China.

X. Fu is with the State Key Laboratory of Semiconductor Lasers, Changchun University of Science and Technology, Changchun, JL 130012, China.

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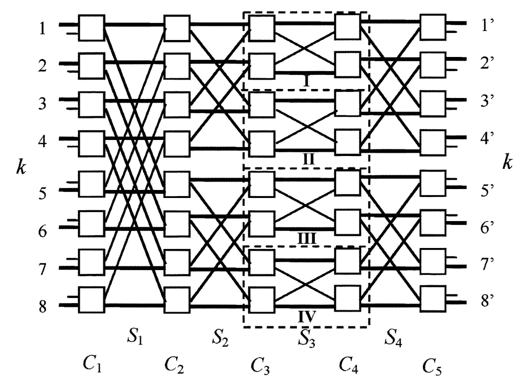

Fig. 1. Construction of 8 × 8 matrix optical switch with the EBN.

II. Analysis for EBN

Fig. 1 schematically shows the construction of an 8 × 8 matrix optical switch of the EBN with butterfly intersection, which is formed by extending the second stage of the basic 8 × 8 Banyan construction. In contrast to the CN construction, which has $2N-1$ signal-passing switching units for an $N \times N$ optical switch, the EBN one has more compact size with only $(2\log_2^N - 1)$ stages of switching units, so an optical signal passes through only $(2\log_2^N - 1)$ stages of switching units from input port to output port. The linking stages and the stages

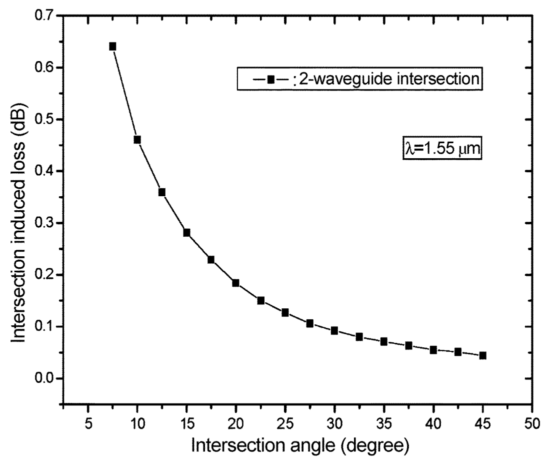

Fig. 2. Simulation results of the intersection-induced optical loss versus the intersection angle θ_{bs}.

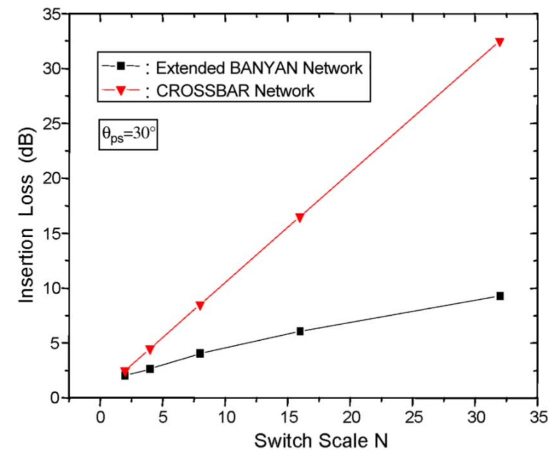

Fig. 3. Simulation results of the IL versus the switch scale N.

of switching units are successively labeled as $S_1, S_2, \cdots, S_4$ and $C_1, C_2, \cdots, C_5$ from left to right, respectively, and the switching units of each stage are numbered as $1, 2, \cdots, N$ from top to bottom. In each stage of the basic Banyan construction, a butterfly line intersects with the $N/2^i$ reverse butterfly lines, and intersects with the $N/2^i - 1$ horizontal lines, where $i = 1, 2, 3$ denotes the linking stage number. Specifically, the orderliness of Banyan construction is helpful for both the mask design and the component fabrication with PLC technology. In the mask design, we have avoided the three-waveguide intersection, i.e., the intersection of two butterfly lines and a horizontal line, by properly designing the layout. Therefore, there are only two types of intersection: 1) the intersection between a horizontal line and a butterfly intersectional line and 2) the intersection between two butterfly lines. Then, the corresponding intersection angles are θ_{bs} and θ_{bb}, respectively, and obviously $\theta_{bs} = \theta_{bb}/2$.

With the simulation software OptiBPM, we simulate the influence of intersection angle on intersection-induced loss with respect to two-waveguide intersecting, as shown in Fig. 2. Note that the intersection-induced optical loss quickly decreases with angle increasing, especially $L_{\text{inter}}(\theta_{bs})$ is 0.09 dB and $L_{\text{inter}}(\theta_{bb})$ is less than 0.01 dB when angle θ_{bs} is 30°, where $L_{\text{inter}}(\theta_{bs})$ and $L_{\text{inter}}(\theta_{bb})$ are the corresponding optical losses of the two types of intersection. Then, the ILs of the optical matrix switches with CN and EBN constructions can be calculated via (1) and (2), respectively [1]

$$\text{IL}_{\text{CN}} = TL_{\text{switch}} + TL_{\text{prop}} + 2L_{\text{WFC}} \quad (1)$$

$$\text{IL}_{\text{EBN}} = TL_{\text{inter}} + TL_{\text{switch}} + TL_{\text{prop}} + 2L_{\text{WFC}} \quad (2)$$

where TL_{inter}, TL_{switch}, TL_{prop}, and L_{WFC} are the total intersection-induced loss, the total switching units loss, the total propagation loss, and the waveguide-fiber coupling loss, respectively. With the switching units length of 1.0 cm, the switching-unit loss of 0.4 dB, the propagation loss of 0.1 dB/cm, and the waveguide-fiber coupling loss of 0.5 dB/facet, the ILs of optical matrix switches based on the two types of networks are simulated, as shown in Fig. 3. It is obvious that the EBN construction has a quite lower IL compared with the CN one. But the power consumption of the EBN construction is relatively larger than that of the CN construction. For an 8 × 8 matrix optical switch, the average power consumption of the CN is approximately 0.5 W/ch, but it is approximately 1.2 W/ch for the EBN construction.

From Fig. 1, we can find that two signals from input ports k and $k + 4$ $(k = 1, 2, 3, 4)$ of stage C_1 to output ports k' and $k' + 1$ $(k' = 1', 3', 5', 7')$ of stage C_5 should go through two of the four groups of link lines at stage S_3 as framed with dashed lines. To avoid the routing blocking, the selections for these two signals to route the correct two groups of link lines at each stage must be governed by a principle. The flow diagram for signal routing process of the EBN construction is depicted in Fig. 4. The vectors $\boldsymbol{I}$ and $\boldsymbol{O}$ are both the (1 × 8) vectors and defined to denote the numbers of input ports and output ports, respectively. Vector $\boldsymbol{D}$ is defined to be the number differences of the input ports of two signals having adjacent output ports, where $\boldsymbol{D}(i) = |\boldsymbol{I}(2i) - \boldsymbol{I}(2i-1)| (i = 1, 2, 3, 4)$. Vector $\boldsymbol{F}$ is defined to mark the signal paths according to the signal output at the switching units of stage C_4, and is set as 1 for the horizontal line output and 2 for the butterfly intersectional line output. $\boldsymbol{R}$ is the matrix for operating the switching units, where the matrix element $\boldsymbol{R}(m, n)$ is 1 when the switching unit of the mth row and the nth column should be activated electrically, otherwise $\boldsymbol{R}(m, n)$ is 0. $\boldsymbol{T}$ is the temporary vector, and i, j, and k are temporary variables. With the flow diagram, for a correspondence of vectors $\boldsymbol{I}$ and $\boldsymbol{O}$, the matrix $\boldsymbol{R}$ could be found as the following description. To find $\boldsymbol{R}$, we should first find the states of switching units of all accessible paths between input and output ports, and these paths can be divided into two classes, respectively tagged by 1 and 2 according to the output ports at the switching units of stage C_4. To avoid the paths blocking, the 1-tagged paths are always chosen when the signals' output ports are 1, 3, 5, and 7. Only when the signals' output ports are 2, 4, 6, and 8, and the number difference of two adjacent signals' output ports is 4, the 2-tagged paths should be chosen, otherwise the 1-tagged paths are also chosen. Finally, the vector $\boldsymbol{R}$ can be obtained according to the acquired paths of all signals and the states of switching units of all paths.

III. Experiments

An 8 × 8 matrix optical switch with the EBN construction and the silica-based PLC technology was fabricated and packaged. A photograph of the die-level device is shown in Fig. 5(a) and its waveguides layout in mask is shown in Fig. 5(b), where

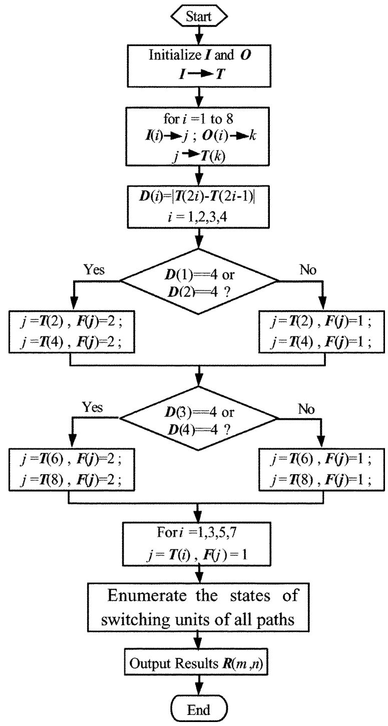

Fig. 4. Flow diagram of the logic grogram for driving the switching units of 8 × 8 matrix optical switch with the EBN.

the main parts of devices are labeled in both the photograph and the waveguides layout. In the design of layout, the distance between two adjacent channels is designed as an industrial standard of 250 μm at the two end areas of layout, while this distance is designed as 100 μm at the middle area to reduce the length of the layout at the horizontal direction, which can be noticed from Fig. 5(b). The die-level chip size was 55 mm × 6 mm. The refractive index difference of waveguide, the cross section size, and the intersection angle are 0.75%, $5.5 \times 5.5\ \mu\text{m}^2$ and 30°, respectively. With the automatic precision aligning mechanism, the fiber arrays having the polished ends were straightly aligned to the polished input and output ends of waveguides for the 1550-nm light signals. The propagation loss of 0.1 dB/cm and the waveguide-fiber coupling loss of 0.5 dB/facet are measured at 1550-nm wavelength. The average insertion loss (IL), average crosstalk (XT), average polarization-dependent loss (PDL), average switching power consumption (SPC), and switching time (ST) were obtained as depicted in Table I. According to the experimental results, the maximal and the minimal IL of 5.63 and 4.46 dB, and the maximal and the minimal SPC of 1.75 and 1.28 W were obtained, respectively. Note that the measured value of IL is closed to what was obtained in simulation and the results of XT and ST are also excellent.

IV. Conclusion

A new rearrangeable nonblocking EBN with width $N = 8$ and its routing process were studied for implementing optical matrix switches. Based on the PLC technology and the EBN construction, we fabricated and packaged a silica waveguide 8 × 8 matrix optical switch. The average insertion loss was 4.6 dB, and the average XT was −38 dB. We also obtained an average PDL of 0.4 dB, an average switching power of 1.6 W/ch, and an ST of less than 1 ms. The fewer stages of the EBN construction make it easy to finish an 8 × 8 matrix optical switch in a 4-in wafer without loop-type layout. It is even foreseeable that a 16 × 16 or 32 × 32 optical matrix switch can also be realized in a 4- or 5-in wafer without loop-type layout by using this construction. Note that the EBN construction will evidently reduce the insertion loss and the component cost of matrix optical switches. Therefore, this network is a promising construction for realizing the large-scale matrix optical switches.

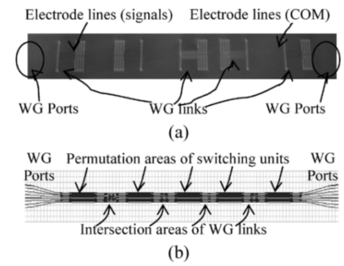

Fig. 5. (a) Photo image of die-level 8 × 8 matrix optical switch with the EBN construction and silica waveguides; (b) waveguides layout, where the abbreviation WG stands for waveguides.

TABLE I
Measured Values of the Performance for the Fabricated 8 × 8 Optical Matrix Switch

Items	IL (dB)	XT (dB)	PDL (dB)	SPC (W/ch)	ST (ms)
Value	4.6	-38	0.4	1.6	1

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