A New 4x4 Wide-Sense Nonblocking Photonic Switching network

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***Abstract*-In this paper, new switch architecture is proposed for nonblocking photonic switching. This switch is a 4x4 space division multistage network using 2x2 optical switch elements, which may be directional couplers, fabricated on titanium diffused lithium niobate (Ti: LiNbO3) substrates. The idea behind the architecture is presented and some properties of the switch are derived and analyzed. The performance of the switch is also discussed and compared with other well-known designs.**

***Index Terms*-Photonic switching, planar architectures, wide-sense nonblocking.**

I. INTRODUCTION

Photonic switching architectures based on 2 x 2 optical switching elements (SEs) are attractive since they can be constructed from directional couplers. The directional coupler switch is a device with two inputs and two outputs, both of which are optical signals [1]. The state of the device (Fig. 1) is controlled electrically by applying different levels of voltage on the electrodes.

Although other materials can be used as a substrate, lithium niobate is the most mature technology for directional coupler optical switch fabrication. A feature of these switches is they can route optical information regardless of its bit rate or coding format [1]. Several directional coupler-based architectures had been proposed in the literature [2,4,5,9,10]. This hybrid device will be the switch element of our optical switching system model in this paper.

There are several criteria for a good switching architecture from system considerations [2]. First, for a given switch size, N, the number of crosspoints should be as small as possible. When the number is large, implementation is expensive and the optical path is subject to large power loss and crosstalk. Second, optical paths should go through equal number of crosspoints to reduce the power variation at the switch output and to avoid the near-far problem. Third, when designed to reduce the crosspoint number in total and in each path, a switch can have a large internal blocking probability. In some switches, the internal blocking probability can be completely reduced to zero by using a good switching control or rearranging the current switching configuration. These cases are called wide-sense nonblocking and rearrangeably nonblocking, respectively [3]. If a blocking condition never arises in a switch it is said to be strictly nonblocking.

In this paper, a nonblocking network is proposed for photonic switching. The architecture is designed based on the idea of the 3-stage Clos topology. Some properties including the number of SEs required, number of crossovers, system attenuation, and signal-to-noise ratio (SNR) are derived. As compared with other well-known networks, most of the properties are shown to be better.

The paper is organized as follows; section II provides an overview of planar switches and explains their importance in the design of directional coupler-based photonic switching systems. In section III, the development of a 2x3 wide-sense planar switch will be presented. How this 2x3 switch is used to construct the new 4x4 wide-sense nonblocking switching network is explained in section IV. The performance of the developed switch compared with other well-known designs is discussed in section V. Section VI concludes the discussion.

II. PLANAR SWITCHES

The N-stage planar switch has a number of crosspoints less than half of that in a single crossbar and a maximum number of crosspoints in a connection path better than that of a double crossbar. Because of the fewer number of crosspoints, one primary disadvantage of the N-stage planar switch is it is rearrangeably nonblocking [5].

The N-stage planar switch has $N/2$ odd stages and $N/2$ even stages (Fig. 2). The odd stages are of $N/2$ SEs each, while the even stages are of $N/2-1$ SEs each. In general an NxN network requires N stages, where N may be even or odd and the total number of SEs is:

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$$SE_S = N/2(N/2 + N/2 - 1) = N/2(N-1) \quad (1)$$

The maximum number of SEs in a connection path is obtained when the optical signal crosses a SE in every stage of the switching system, that is, when it crosses N SEs. Fig. 2 shows a planar switch of size 3.

III. WIDE-SENSE NONBLOCKING

An algorithm for deciding whether a given network is nonblocking or not is described in [7]. Using this algorithm we can prove that the 3x3 switch of Fig. 2 is blocking. Actually all N-stage planar switches are blocking unless rearranged.

Now, let us use only two inputs of Fig. 2 instead of all its three inputs. This gives the 2x3 switch shown in Fig. 3. Again we can use the same algorithm to decide if this switch network is nonblocking. Because the switch network is simple and small, we can *manually* study all its possible states on paper. However, both methods lead to the same outcome. That is, the network is nonblocking in the wide sense if all the states in which SE A is cross (x) and SE B is bar (=) are avoided. In other words, if SE A is in the cross state we should not allow SE B to be in a bar state and vice versa. Such a state, which can cause blocking for a network, is said to be a forbidden state. The set of states of the network that allow any switching we require without bringing the network into a forbidden state was called preservable by Benes [3]; we also refer to the states of this set as preservable states. The preservable state of the 2x3 network is given in Fig. 5a. The state of the last SE does not affect the state of the network and this why it is left blank.

If we use the outlets as inlets and the inlets as outlets the network will be a 3x2 switch (Fig. 4) with the same nonblocking rule still applying. The only different being that SE A and SE C interchanged their positions. The preservable state for this switch is shown in Fig. 5b. The elements of Fig. 3 and Fig. 4 will be called 2W3 and 3W2 respectively.

IV. THE SWITCH ARCHITECTURE

The wide-sense nonblocking switches of Fig. 3 and Fig. 4 are symbolized in Fig. 6. The structure of a 4x4-switching network employing elements of Fig. 6 is presented in Fig. 7. The network consists of two 2W3 switches, three 2x2 switches, and two 3W2 switches. The proposed architecture is constructed based on the same idea of the 3-stage Clos network but in our case -of course- we have more stages because we are using the 3-stage network elements 2W3 and 3W2 in correspondence to the elements of the first and the last stage of Clos network respectively. We call this network a 4W4 switch.

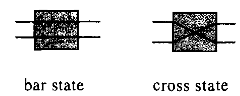

Fig. 1. The states of a 2x2 switch element

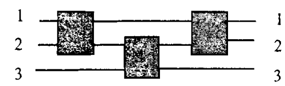

Fig. 2. A 3x3 planar switch .

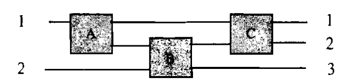

Fig. 3. A 2x3 planar switch

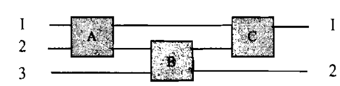

Fig. 4. A 3x2 planar switch

V. SOME PROPERTIES OF THE PROPOSED NETWORK

A. Nonblocking Characteristics

The proposed network is shown to be nonblocking in the wide-sense by the following properties:

Lemma 1 *The 2W3 and 3W2 elements are wide-sense nonblocking.*

It is proved in section II that if these elements follow the algorithm given in Fig. 5, any future connection can always be made without additional rearrangement of the existing paths.

Lemma 2 *The architecture guarantees that the network is free of internal blocking.*

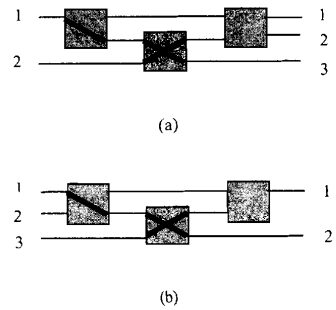

Fig. 5. The preservable states for: (a) the 2x3 switch and (b) the 3x2 switch

Fig. 6. The symbol for: (a) the 2x3 switch and (b) the 3x2 switch

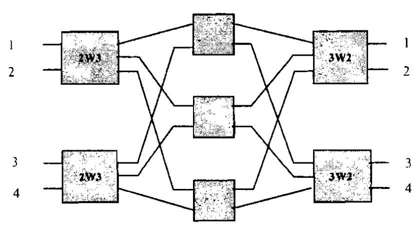

Fig. 7. A 4x4 wide-sense nonblocking network

This is true because the network follows the same idea of the 3-stage Clos architecture and therefore a free path always exists to connect a new call.

B. Total Number of Switching Elements

The complete diagram of the proposed network is shown in Fig. 8. It have seven stages each with two SEs except the middle one which have three SEs, so the total number SEs is: $6\times 2+3=15$.

C. System Attenuation

The system attenuation of an optical network is determined primarily by the insertion loss of the architecture. For simplicity, we ignore the effect of the crossover factor, which is less significant to the system attenuation. The insertion loss is dependent upon the number of SEs that a connection must travel. A switch in $LiNbO_3$ has an insertion loss *L*, in dB, associated with it. An additional attenuation occurs due to waveguide-to-fiber coupling and is represented by *W*, in *dB*. Typically, $L = 1\text{dB}$ and $W = 1\text{-}2\text{ dB}$ [10].

Each connection on the proposed network has to travel across a number of 5 SEs in the worst case (according to the nonblocking algorithm, a signal can not travel across all the three SEs of the 2W3 or the 3W2 element). Thus, the maximum insertion loss for the network is:

$$IL = 5.L + 2.W \tag{2}$$

D. Signal to-Noise Ratio

Each SE that signal passes through introduces a small amount of crosstalk from other channel into the desired signal channel. The signal-to-noise ratio (SNR) for an optical switch can be estimated by determining the number of SEs that the signal passes through and how much power will be leaked into the signal channel at each point.

For the proposed network and again because of the nonblocking algorithm, the total number of SEs that can cause crosstalk in the worst case is only three. These SEs are, the middle stage SE plus the second or third stage SE of the 2x3 and the fifth or sixth stage SE of the 3x2 element.

Let $P_{out(i)}$ represent the total power in dB of a signal that arrives at a given outlet *i*. Thus,

$$P_{out(i)} = P_{in(i)} - IL \tag{3}$$

where $P_{in(i)}$ is the power in dB entered into inlet *i* and *IL* is the system insertion loss. The noise that enters the outlet is the sum of the noise power that enters in the form of crosstalk. In the worst case, the noise that enters the outlet *i* from inlet *j* can be calculated as,

$$P_n(i,j) = P_{n(j)} - X - IL \tag{4}$$

The total noise in the outlet *i* is the sum of the noise power caused by 3 channels (since there are at most three SEs which may cause a crosstalk in the path). Therefore, we have

$$P_n(total)[Watts] = 3.P_n(i,j)[Watts] \tag{5}$$

Converting into decibels gives

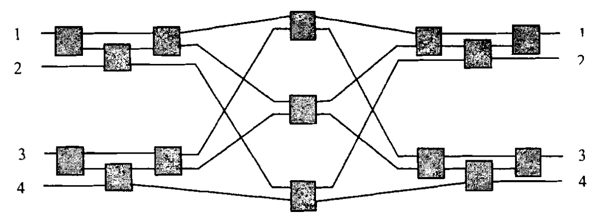

Fig. 8. The complete diagram of the 4x4 switch

$$P_n(total)[dB] = 10\log_{10} 3 + P_n(i,j)[dB] \tag{6}$$

The worst case SNR is

$$SNR = P_{out(i)} - P_n(total) \tag{7}$$

By equations (3), (4), and (6), we have

$$SNR = X - 10\log_{10} 3 \tag{8}$$

E. Maximum Number of Crossovers Between an Inlet-Outlet Pair

The number of crossovers in a single substrate optical switch has an important influence on the performance [8]. Crossovers may cause crosstalk, signal loss, and design complexity. The maximum number of crossovers that a path for an inlet-outlet pair must travel is related to the worst case system attenuation and the SNR. From Fig. 6, and as a worst-case, the maximum number of crossovers that can be traveled by a signal along the inlet-outlet path is 4, i.e. when input 1or 2 (3 or 4) are connected to output 1 or 2 (3 or 4) through the lower (upper) 2x2 center switch. In the best cases, however, signals can travel along completely crossover free paths.

VI. Performance Analysis and Comparison

Several photonic switching architectures are compared with the proposed network. They are the optical crossbar, the N-stage planar, the Benes, the 3-stage Clos, and the Extended Baseline. Most of these networks have been analyzed and compared in the literature [4,9]. We compare them further with our network (which we referred to as 4W4) in the following subsections.

A. Blocking Characteristics

A summary on the blocking characteristics for the above mentioned networks are shown as follows.

Network	Nonblocking type
Crossbar	Wide-Sense
N-Stage Planar	Rearrangeable
Benes	Rearrangeable
3-Stage Clos	Strictly
Extended Baseline	Strictly
4W4	Wide-Sense

B. Number of SEs Required

The number of SEs required in each type of 4x4 optical network is given as.

Network	Number of SEs required
Crossbar	$N^2 = 16$
N-Stage Planar	$N.(N-1)/2 = 6$
Benes	$(N/2).(2\log N - 1) = 6$
3-Stage Clos	$2.n.m.r + mr^2 = 36$
Extended Baseline	$(3.N^2/2 - (5.N/2) = 14$
4W4	$4 \times 3 + 3 = 15$

The Benes and the *N*-stage planar networks require fewer couplers than the others. However, they are rearrangeably nonblocking and therefore a more complex control algorithm is needed for establishing a new connection. The 3-stage Clos network is made up by $n \times m$ subnetworks at the first stage, $r \times r$ subnetworks at the middle stage, and $m \times n$ subnetworks at the last stage. It can be shown that $N=r.n$. It is also well known that a 3-stage Clos network is nonblocking if $m=2n-1$. For $n=2$, we obtain $m=3$ and $r=2$ hence, 2x3 and 3x2 subnetworks are needed in the first and last stage of a 4x4 network respectively. We assume crossbar switches are used in each stage.

C. Insertion Loss

The system insertion loss in dB for each network is given below where $L = 1dB$ and $W = 2dB$. According to [10], the maximum attenuation allowed from system input to output without amplification or regeneration is assumed to be 30 dB.

Network	Insertion Loss
Crossbar	$(2N-1).L+2.W=11$
N-Stage Planar	$N.L+2W=8$
Benes	$(2\log_2 N).L+2.W=8$
3-Stage Clos	$(2.n+2.m+2.r-3).L+6.W=23$
Extended Baseline	$(3.\log_2 N-1).L+2W=9$
4W4	$5.L+2.W=9$

The N-stage planar and the Benes networks have lower insertion loss than the 4W4 network, which has the same *IL* performance as the extended baseline network. However, the planar and the Benes networks are rearrangeably nonblocking while the extended baseline has more crossovers. Since the 4W4 network results in a far lower IL from the assumed constrain of 30 dB, it is possible to apply the design idea for larger size networks.

D. Signal -to- Noise Ratio

The SNR in dB for each network is given below, where the extinction loss is assumed to be 20 dB. To achieve a bit error rate of lower than 10^{-9}, the required SNR should, roughly, be greater than 11 dB (10). The 4W4 has the same SNR performance as the crossbar, Benes, and the Extended baseline, which is the best among the given designs. When the SNR of the 4W4 is assumed to be 11 dB, the achievable switch dimension can be larger than 4.

Network	SNR
Crossbar	$X-10\log_{10}(N-1)=15.2$
N-Stage Planar	$X-10\log_{10}N=14$
Benes	$X-10\log_{10}(2\log_2 N-1)=15.2$
3-Stage Clos	$X-10\log_{10}(n+m+r)=11.5$
Extended Baseline	$X-10\log_{10}(2\log_2 N-1)=15.2$
4W4	$X-10\log_{10}3=15.2$

E. Number of Crossovers

The maximum number of crossovers between an inlet-outlet pair for each design is given below.

Network	Max. No. of Crossovers
Crossbar	0
N-Stage Planar	0
Benes	$(2.N-2\log_2 N-2)=2$
3-Stage Clos	$2.(m-1).(r-1)=4$
Extended Baseline	$4.N-3\log_2 N-5=5$
4W4	4

The crossbar, planar, and Benes have the best performance. However, the crossbar requires more SEs while the other two are rearrangeably nonblocking. The 4W4 has the same performance as the 3stage Clos, which is better than the extended baseline performance. Table 1 shows the comparison results all together.

TABLE I
PERFORMANCE RESULTS FOR VARIOUS TYPES OF 4x4 PHOTONIC SWITCHING NETWORKS

Network	Nonblocking Type	Number of SEs	Insertion Loss (dB)[a]	SNR (dB)[b]	Number of Crossovers
Crossbar	Wide-Sense	16	11	15.2	0
N-Stage Planar	Rearrangeable	6	8	14	0
Benes	Rearrangeable	6	8	15.2	2
3-Stage Clos	Strict-Sense	36	23	11.5	4
Extended Baseline	Strict-Sense	14	9	15.2	5
4W4	Wide-Sense	15	9	15.2	4

[a] Assuming L=1 dB and W=2 dB.
[b] Assuming X=20 dB.

VII. CONCLUSION

In this paper, a new architecture for a 4x4 photonic switching network has been proposed. The architecture is shown to be wide-sense nonblocking. Some characteristics of the proposed network as well as other well-known topologies are analyzed and compared. The results indicate that the proposed network is better when several important criteria are considered simultaneously.

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REFERENCES

[1] D. K. Hunter, " Optical Switching in Ultrafast Communications Networks", *PhD Dissertation*, University of Strathclyde, Glasgow G1 1XW, 1991.

[2] M. M. K. Liu, *Principles and Applications of Optical Communications*, Richard D. Irwin Inc. Company, 1996

[3] V. E. Benes, *Mathematical Theory of Connecting Networks and Telephone Traffic*, Academic Press, 1965.

[4] R. A. Spanke, "Architectures of Guided-Wave Optical Space Switching Systems," *IEEE Comm. Magazine*, vol. 25, no. 5, pp42-48, 1987.

[5] R. A. Spanke and V. E. Benes, "An N-sage Planar Optical Permutation Network," *Applied Optics*, vol. 26, no. 7, pp. 1226-26, 1987.

[6] F. M. Suliman *et al*, "On (N+1)-Stage Planar Photonic Switches," *Proc. National Conference on Telecommunication Technology2000* (NCTT2000) Malaysia, pp C22-C25, November 2000

[7] C. J. Smith, 'Nonblocking Photonic Switch Networks,' *IEEE Journal on Selct. Areas in Comm.*, vol. 6 no. 7, pp 1052-62. August 1988.

[8] C. T. Lea, "Crossover Minimization in Directional-Coupler-Based Photonic Switching System," *IEEE Trans. Commun.* vol. 36, no. 3, pp. 355-363, March 1988.

[9] Andrzej Jajzczyk, "A Class of Directional-Coupler-Based Photonic Switching Networks," *IEEE Trans. Commun.* vol. 41, no 4, pp 599-603, April 1993.

[10] Chiung-Shien Wu *et al*, "A New Nonblocking Network for Photonic Switching," *0-7803-3336-5/96 $5.00 ©1996 IEEE*