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A 4x4 Space Dilated Lightwave Network–A New Approach

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***Abstract*—In this paper, the space dilation concept for reducing crosstalk in Ti:LiNbO$_3$ directional-coupler-based photonic switches operating at a single wavelength is applied using a new approach. A new method for minimizing the switch crosstalk is described. A novel 4x4 switch architecture is proposed for nonblocking photonic switching networks to fully exploit the advantages of this method. Some properties of the switch architecture are derived and analyzed. The performance of the switch is also discussed and compared with other well-known network architectures.**

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 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].

Performance of optical architectures may be characterized by the following parameters:

1. Optical path loss (worst case)
2. Crosstalk (worst case)
3. Total number of couplers required.

The attenuation of light passing through the optical architecture is directly proportional to the number of couplers that the optical signal passes through. Therefore, for the purposes of this paper, the number of couplers in an inlet-outlet path will be used to characterize the optical path loss.

There are two ways in which optical paths can interact with each other in a planar switching network causing optical crosstalk. The channels (wave-guides) carrying the signals could cross each other in order to imbed a particular topology. This is called channel crossover. Alternatively, two paths sharing a switching element will experience some undesired coupling from one path to the other. This is called the switch crosstalk. The channel crossover however can be made negligible if the intersection angle is greater than 3°[4]. Thus, we will assume that switch crossovers are the major source of crosstalk in optical switching networks constructed out of directional couplers.

The spatial dilation concept for reducing crosstalk in switches operating at a single wavelength is well known. By adding more switches and switching signals via paths where only one signal is active it have been shown that the crosstalk can be reduced. The dilated-Benes architecture was suggested in [6]. Fig. 1 illustrates the dilation principle. A 2 x 2 basic element switch is shown together with its dilated version. If ε denotes the crosstalk intensity for the 2 x 2 basic element switch, it is straightforward to show that the dilated version exhibits crosstalk of O (ε^2).

The principal contribution of this paper is a novel architecture for a 4x4 nonblocking multistage space photonic switch implemented using Ti:LiNbO$_3$ directional couplers. The network utilizes a new approach of space dilation that guarantees connections between inputs and outputs with minimum switch crossovers and hence reduced crosstalk. Some properties of the network 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 network architectures, most of the properties show significant improvement.

The paper is organized as follows; section II provides an overview of the basic element of our new architecture. We explain how to design them and how the new approach of space dilation is applied to them. In section III, the development of the 4x4 nonblocking switching network architecture is explained. The performance of the developed switch compared with other well-known designs is discussed in section IV. Section V concludes the discussion.

II. THE NEW APPROACH

The N-stage planar switch has N/2 odd stages and N/2 even stages. The odd stages are of N/2 SEs each, while the even stages are of N/2 – 1 SEs each. In general an N x N planar network requires N stages, where N may be even or odd. Fig. 2 illustrates a 3x3 N-stage planar switch.

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. In Fig. 2, in the worst case, all the three switches crossed by the signal contribute to the total -first order- crosstalk.

An algorithm for deciding whether a given network is

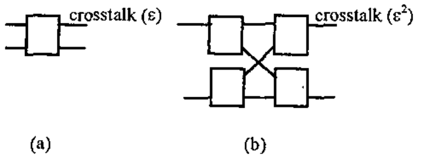

Fig. 1. (a) A 2 x 2 switch and (b) its space-dilated version

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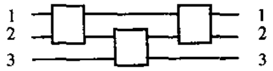


Fig. 2. A 3 x 3 planar switch.

nonblocking or not is described in [7]. Using this algorithm we can prove that the 3x3 switch of Fig. 2 is blocking unless rearranged.

If only two inputs of Fig. 2 are used instead of all its three inputs, this gives the 2x3 planar switch shown in Fig. 3. For this switch only two switches contribute to the worst-case total crosstalk. 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 get into 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.

Examining Fig. 5(a) it can be noted that in all cases the input signals are not allowed to share more than one SE when traveling toward their destinations. Therefore, it is this single switch that causes the first order crosstalk.

In Fig. 3, if we use the outlets as inlets and the inlets as outlets (i.e. flipping the switch horizontally), the network will be a 3x2 switch (Fig. 4) with the same nonblocking rule still applicable. The preservable state for this switch is shown in Fig. 5b. The input signals also share only one coupler toward their destinations in the worst case.

TABLE 1

CROSSTALK PERFORMANCE FOR THE POSSIBLE CONNECTIONS OF THE 2 X 3 SWITCH

Number	Connection	Crosstalk
1.	1-1, 2-2	Yes
2.	1-1, 2-3	No
3.	1-2, 2-1	Yes
4.	1-2, 2-3	No
5.	2-1, 1-2	Yes
6.	2-1, 1-3	Yes

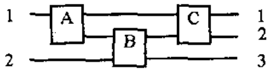


Fig. 3. A 2 x 3 planar switch

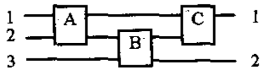
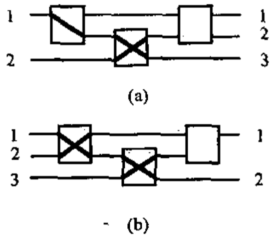


Fig. 4. A 3 x 2 planar switch



(a)

(b)

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

This is because no more than two signals can be applied at their inputs (no output contention). It should be noted how the number of couplers which contribute to the total crosstalk have been reduced from three in Fig. 2 to only one in Fig. 5. Furthermore, as shown in Table 1, one third of the possible connections of the 2 x 3 switch can be setup with zero crosstalk in the best cases. The 2 x 3 and the 3 x 2 switches will be used to construct the new 4x4 nonblocking photonic switch architecture.

III. THE SWITCH ARCHITECTURE

The wide-sense nonblocking switches of Fig. 3 and Fig. 4 will be called 2W3 and 3W2 respectively. They are symbolized in Fig. 6. The proposed architecture is constructed by adapting the idea of the Clos network. 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 stages of the Clos network respectively.

The 4x4 switching network employing the 2W3 and 3W2 elements is presented in Fig. 7. The network consists of two 2W3 input switches, three 2x2 subnetwork switches, and two 3W2 output switches. The 2W3 and 3W2 switches are shown inside dashed boxes. We call this network a 4W4 switch. Actually this 4 x 4 switch represents the smallest network that can exploit the advantages of this space dilation approach. The basic 2x2 SE represents the smallest possible subnetwork. Similar NxN networks were addressed in [11].

IV. 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.

(a) (b)

Fig. 6. The symbols for (a) the 2 x 3 and (b) the 3 x 2 switch

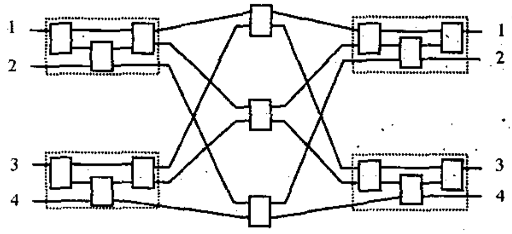


Fig. 7. A 4 x 4 wide-sense nonblocking network, 4W4

Lemma 2 *The architecture guarantees that the network is free of internal blocking.* 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 as shown in Fig. 7 has seven stages each with two SEs except the middle one which has three SEs, so the total number of 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 $W = 1\text{-}2$ 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:

$$IL = 5.L + 2.W \tag{1}$$

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,

$$P_{out(i)} = P_{in(i)} - IL \tag{2}$$

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,

$$P_n(i,j) = P_{in(i)} - X - IL \tag{3}$$

Where *X* is the extinction ratio of the switch element. 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

$$P_n(total)[Watts] = 3.P_n(i,j)[Watts] \tag{4}$$

Converting into decibels give

$$P_n(total)[dB] = 10\log_{10} 3 + P_n(i,j)[dB] \tag{5}$$

The worst case SNR is

$$SNR = P_{out(i)} - P_n(total) \tag{6}$$

By equations (2), (3), and (5), we have

$$SNR = X - 10\log_{10} 3 \tag{7}$$

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.

V. 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 the 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	$2.n.m.r + m.r^2 = 36$
Extended Baseline	$(3.N^2/2-(5.N/2) = 14$
4W4	$4\times3+3 = 15$

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* x *m* subnetworks at the first stage, *r* x *r* subnetworks at the middle stage, and *m* x *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 of the Clos network.

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	$N.L+2.W = 8$
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	$(3.\log_2 N-1).L+2.W = 9$
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

TABLE 2
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.

performance as the 3-stage Clos, which is better than the extended baseline performance. Table 2 shows the comparison results all together.

VI. 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 are analyzed and compared with other well-known topologies. The results indicate that the proposed network is better when several important criteria are considered simultaneously.

The main disadvantage of the proposed network is the variation of the number of SEs crossed by the input signals when traveling toward their destinations. This is inherited from the planar topology, which is adopted in the design of the 2x3 and 3x2 elements. On the element level, however, and because of the preservable states described for these elements, the effect of the drawback is kept to minimum. From Fig. 5 it can be noted that only one connection per each element experiences this effect, namely when input 2(3) is connected to output 3(2) in the 2 x 3 (3 x 2) element. All other connections equally cross two SEs. On the system level (Fig.7) attenuators can be used when necessary. When used, attenuators should attenuate the signal by a factor equal to the insertion loss of the *missing* SEs along the signal path. The factor is either L or $2L$ depending on from which input the signal originated, which route it took, and for which output it was destined.

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