A Multicast Photonic Switching Network

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Abstract--In this paper, a multicast photonic switching network is proposed. The switch is a space division multistage network using 2x2 optical switching elements. The idea behind the proposed architecture and a recursive definition for it are presented. Some properties of the switch are derived and analyzed. The performance of the switch is also discussed and compared with other designs.

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. The state of the device is controlled electrically by applying different levels of voltage on the electrodes [1].

Although other materials can be used as a substrate, lithium niobate is the most mature technology for directional coupler optical switch fabrication. Several directional coupler-based architectures had been proposed in the literature [2,3,4,7,8].

In this paper, a multicast photonic network is proposed for photonic switching. The architecture is built based on 2 x N multicast switches. Some properties including the number of SEs required, number of crossovers, system attenuation, and signal-to-noise ratio (SNR) are derived.

The paper is organized as follows; section II presents the architecture of the proposed network. We explain how to design it using 2 x N multicast switches. In section III, some properties of the switching network are derived. The performance of the proposed network compared with other well-known designs is discussed in section IV. Section V concludes the discussion.

II. THE MULTICAST PHOTONIC NETWORK

Some multicast switches capable of realizing all possible connection patterns of Fig. 1[7] are shown in Fig. 2. The last stage of switches is necessary to realize the last connection given in Fig. 1. The 1:N passive splitters used in the 2 x N switch can be implemented as tree structures composed of 1:2 passive splitters.

The 2 x N switch of Fig.2 (b) (without the last stage) will be used to construct the proposed network.

To design any N x N multicast switch where $N=2^n$, n is an integer and $n \geq 1$, we need:

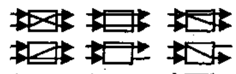

Fig. 1 All possible connection patterns in a 2 x 2 switch

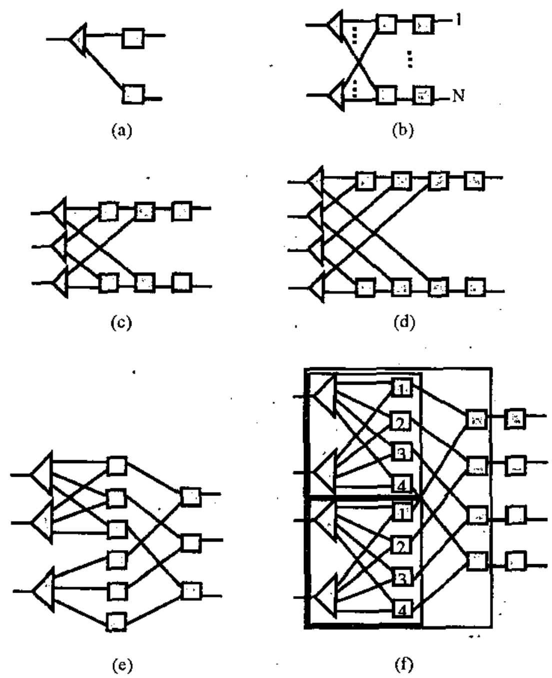

Fig. 2 Photonic multicast switches: (a) 1x 2; (b) 2 x N; (c) 3 x 2; (d) 4 x 2; (e) 3 x 3; and (f) 4 x 4 switch

- A total number of $\log_2 N+2$ stages.
- N 1:N passive splitters at stage 0.
- $N^2/2$ 2:1 switch elements at stage 1.
- $N^2/4$ 2:1 switch elements at stage 2.
- ...
- $N^2/N=N$ 2:1 switch elements at stage $\log_2 N$.
- N 1:1 switch elements at stage $\log_2 N+1$.

The design idea can also be stated in a recursive grouping fashion as: any NxN switch is actually N/2 groups of 2xN switches each at stage 1 linked into N/4 groups of 4xN

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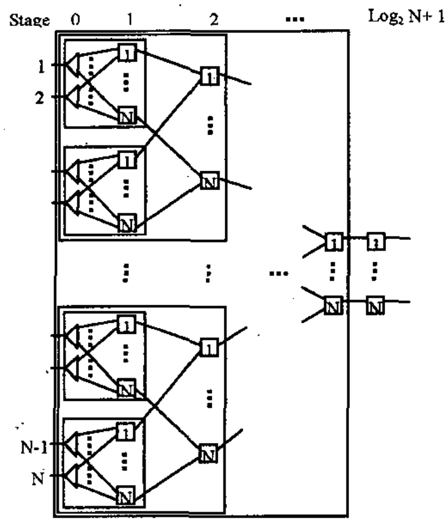

Fig. 3 The proposed N x N multicast photonic switch, NMN

switches each at stage 2 then into N/8 groups of 8xN switches each at stage 3 and so on until they form one group (N/N) at the second last stage. Then the last stage is simply cascaded. In Fig. 2 (f) and Fig. 3 this grouping approach is represented using boxes. To illustrate an example, the 4 x 4 switch of Fig. 2 (f) consists of two groups of 2 x 4 switches linked together at stage 2 forming the 4 x 4 group. The last stage is then added to make the full-multicast switch. It should be noted that with slight modifications to the above mentioned steps any N x M networks (Fig 2 (c) and (d)) and any networks with odd values of N (Fig. 2 (e)) can also be designed. However they are not considered in this paper.

III. Some Properties of the Proposed Network

A. Nonblocking Characteristics

The use of passive splitters in the proposed network ensures the connection of any inlet to any unused outlet without rearrangement regardless of the connecting algorithm used. Therefore it is nonblocking in the strict sense.

B. Total Number of Switching Elements

Observing Fig. 3, the calculation of the total number of SEs for the proposed network is straightforward. It is equal to the sum of the SEs in $\log_2 N$ stages (or in all groups) plus The SEs of the last stage. Therefore, The total number of SEs required, SE_T, is:

$$SE_T = N + N \sum_{i=1}^{\log_2 N} (N/2^i) = N^2 \quad (1)$$

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=1dB and W=1-2 dB [3].

If fabricated on a single substrate, each connection on the proposed network has to travel across $\log_2 N$ 1:2 passive splitters and $\log_2 N+1$ directional couplers. With the excess loss in each passive splitter represented by E, the maximum insertion loss for the network is given by:

$$IL = \log_2 N(3+E) + (\log_2 N + 1)L + 2W \quad (2)$$

The 3 dB figure represents the 50/50 power split [7]. Here, fiber devices are assumed for passive splitters.

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. The SNR is calculated using an approach similar to that in [7] and [8].

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

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

Where $P_{in}(i)$ is the power in dB entered into inlet i and IL is as given in formula (2). 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, $P_N(i,j)$, can be calculated as,

$$P_N(i,j) = P_{in}(i) - X - IL \quad (4)$$

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 $\log_2 N$ channels (see Fig. 3). The noise caused by the other $N-\log_2 N$ channels is ignored because it passes with better extinction ratios. Therefore,

$$P_N(total)[Watts] = (\log_2 N).P_N(i,j)[Watts] \quad (5)$$

Converting into decibels gives

$$P_N(total)[dB] = 10\log_{10}(\log_2 N) + P_N(i,j)[dB] \quad (6)$$

The worst case SNR is

$$SNR = P_{out}(i) - P_N(total) \quad (7)$$

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

$$SNR = X - 10\log_{10}(\log_2 N) \quad (8)$$

E. Number of Crossovers

The number of crossovers in a single substrate optical switch has an important influence on the performance [5]. 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.

Observing Fig. 3, the total number of link stages is $\log_2 N+1$ with only $\log_2 N$ stages having crossovers. It can be noticed that the links are grouped into N/2 groups at the first stage then reduced to half at each following stage of links. The total number of link groups is N–1. Each link group has N/2(N–1) crossovers. Then for the network the total number of crossovers is $N/2(N-1)^2$. It can be shown that the maximum number of crossovers that can be traveled by a signal along the worst-case inlet-outlet path is $(N-1)\log_2 N$. All calculations of crossovers were carried based on 1:N passive splitters. If 1:2 splitters are used the total and maximum number of crossovers will be reduced to $(N-1)^2$ and $N(\log_2 N-1)+1$, respectively.

F. Number of Drivers

Examining the first two adjacent groups of Fig. 3 or Fig. 2(f), we can note that every pair of like-numbered switches can be driven with one driver. This can be done for every two adjacent groups in all stages (that have at least two groups). This is true because the two switches in every pair are linked to the same switch in the next stage. It is the responsibility of this destination switch to decide which one of them to connect. The state of the unconnected one does not matter. The like-numbered switches, therefore, can be changed to the same state simultaneously. Thus, the number of drivers needed for every stage (except the last two stages) of switches is half the number of switches in that stage.

Excluding the last two we have $\log_2 N-1$ stages of switches on which this technique can be applied. The total number of drivers needed is equal to the sum of the drivers used in $\log_2 N-1$ stages plus the drivers of the last two stages.

Therefore, The total number of drivers required, D_T, is:

$$D_T = 2N + (N/2)\sum_{i=2}^{N/2}(N/i) = (N^2/2) + N \quad (9)$$

IV. Performance Analysis and Comparison

Some multicast $LiNbO_3$-based photonic switching architectures are compared with the proposed network (NMN) in the following subsections. They are the conventional tree type (with passive splitters and active combiners), Jajszczyk's two-active-stage nested, and non-nested networks. Most of these networks have been analyzed and compared in the literature [3,5,7]. Other topologies - like those based on Semiconductor Optical Amplifiers (SOA) - are beyond the scope of this paper.

A. Blocking Characteristics

All the above-mentioned networks are nonblocking in the strict sense. The conventional tree type, however, cannot realize all connection patterns shown in Fig. 1.

B. Number of SEs Required

The number of SEs required in the conventional tree type network is $N(N-1)$. It is fewer than that required in each of the other types. They require N^2 couplers.

C. Insertion Loss

The system insertion loss in dB for each network is plotted in Fig. 4, where we assume L=1dB and W=2dB. The maximum attenuation allowed for the system without amplification or regeneration is assumed to be 30 dB [3,8].

The conventional tree type network has the lowest insertion loss. However the NMN network shows better performance than the two active-stag networks. Since the NMN network results in a far lower IL from the assumed constrain of 30dB, it is possible to design larger size networks (≈128).

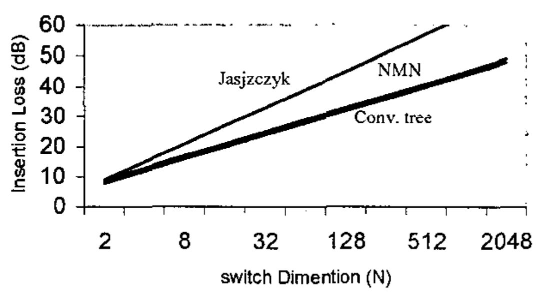

Fig. 4 The system insertion loss for various multicast network topologies

D. Signal -to- Noise Ratio

The SNR in dB for each network is plotted in Fig. 5. The extinction loss is assumed to be 20 dB. To achieve a bit error rate of lower than 10^{-9}, the required SNR should be greater than 11dB (rough approximation)[3]. The NMN and the conventional tree-type have the same SNR performance, which is better than that of Jasjczyk's two active-stage designs. When the SNR of the NMN is assumed to be 11 dB, the achievable switch dimension can be as large as 256.

E. Number of Crossovers

The total number of crossovers in each design is plotted in Fig. 6 with the NMN network showing the best performance. The maximum number of crossovers between an inlet-outlet pair for each design is plotted in Fig. 7. The Jajzczyk,s nested network has the best performance followed by the NMN network. As mentioned in section II, the maximum number of crossovers between an inlet-outlet pair can be reduced if 1:2 passive splitters are used.

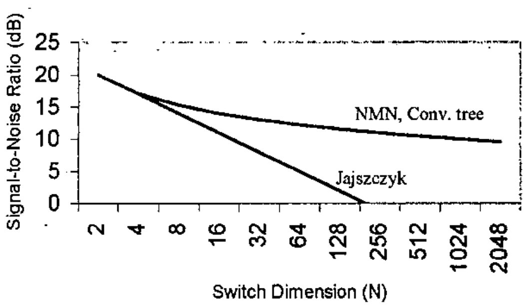

Fig. 5 The signal-to-noise ratio for various multicast network topologies

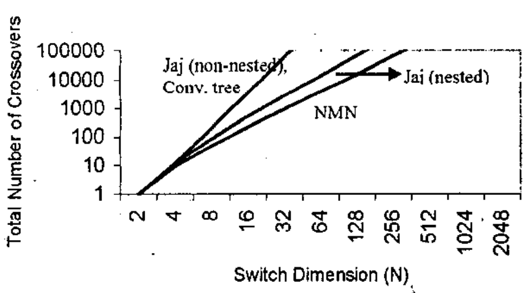

Fig. 6 The total number of crossovers for various multicast network topologies

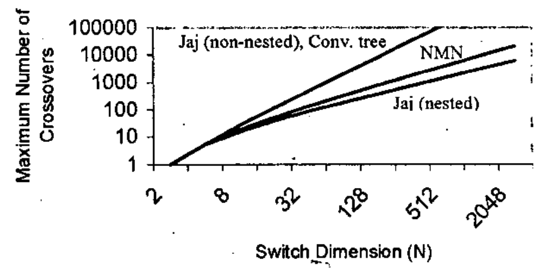

Fig. 7 The maximum number of crossovers between an inlet outlet pair for various multicast network topologies

V. CONCLUSION

A multicast photonic switching network has been proposed. Some characteristics of the proposed network are analyzed and compared to other well-known multicast $LiNbO_3$-based topologies. The results indicate that the proposed network has the lowest total number of crossovers. It shares the highest SNR together with the conventional tree type. It also shows a moderate insertion loss performance.

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