Array Interconnection for Rearrangeable 2-D MEMS Optical Switch

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***Abstract*—Two-dimensional (2-D) microelectromechanical systems (MEMS) optical switches can be constructed by arranging the MEMS-actuated micromirrors as an array. We consider here the switching capability, routing, and optimization of the rectangular array interconnection on which the capability and efficiency of 2-D MEMS switches depend. The switching capability of a rectangular array is proved analytically. Two routing algorithms, namely, the most-bend routing and the least-bend routing, are developed, which, respectively, maximize and minimize the number of 2 × 2 switches in the "bend" state. A method of counting the number of permutations realizable with a given number of switches in the "bend" state is proposed to evaluate the performance of both routing schemes. The understanding of the underlying interconnection pattern enables us to study the problem of constructing rearrangeable optical switches of arbitrary size.**

***Index Terms*—Interconnection networks, microelectromechanical systems (MEMS), optical switches, optimization, rearrangeable, routing control.**

I. Introduction

With the growth of network traffic on the Internet, wavelength-division-multiplexed (WDM) networks are emerging as the core system in major telecommunication transport networks. Advances in optical switching technology further increase the capability of the WDM networks, enabling transparent switching of optical signals. Optical switching based on various technologies, e.g., electrooptic material, interferometer, acoustooptic interaction, thermocapillary effect and microelectromechanical system (MEMS), have been proposed and studied [1]–[11]. Of these, optical switches based on reflections of light beams by MEMS-actuated mirrors promise low loss, negligible crosstalk, and relative maturity of the technology [1]–[4].

In a 2-D MEMS optical switch, the mirrors are so positioned that they can bend light beams by 90°, as shown in Fig. 1. Each mirror can rotate in one dimension so that its reflecting plane stays either parallel (flipped "down" for a light beam to pass through) or perpendicular (flipped "up" to reflect a light beam) to the base plane to which it attaches. This is illustrated in Fig. 1 by the mirrors marked A and B, respectively. By allowing the mirrors to reflect light on both sides, each mirror can be viewed as a 2 × 2 switch, as shown in Fig. 2. The fabrication of two-sided micromirrors has been discussed in [12]. Several optical switch architectures based on 2 × 2 switching elements have been proposed in [13]–[20]. These may not be suitable for 2-D MEMS optical switch because the reflected light beam from a 2 × 2 switch in a MEMS switch propagates to another 2 × 2 switch through free space. This limits the way various switches are interconnected where the imaginary "links" interconnecting the switches are either horizontal or vertical. This implies that not only the interconnection pattern but also the positioning of the micromirrors would matter in the architectures for 2-D MEMS optical switch.

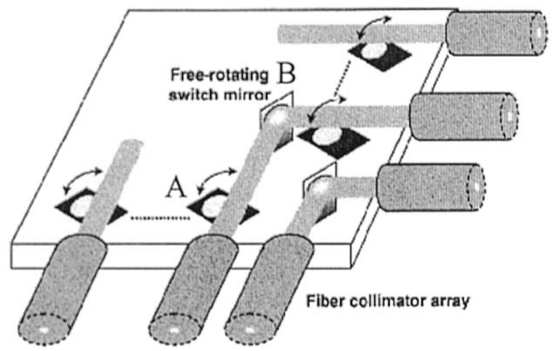

Fig. 1. MEMS-based optical switch.

Fig. 2. Rotating mirror as a 2 × 2 switch.

In this paper, we focus on *array interconnection*. Array interconnection is particularly suitable for 2-D MEMS optical switch in that the 2 × 2 switching elements are interconnected by horizontal and vertical links. In its simplest form, it takes a rectangular shape, as shown in Fig. 3. Array interconnection of 2 × 2 switches can become a useful optical switch architecture only if it is at least *rearrangeable*. A rearrangeable (or rearrangeably nonblocking) switch is one that can realize an arbitrary permutation of its inputs into its outputs, possibly by removing some existing connections. If an arbitrary permutation can be realized without removing any existing connection, the switch is said to be *strictly nonblocking*. Although removing existing connec-

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tions is not desirable, a rearrangeable optical switch may still be practical in a circuit-switched WDM network if it is one where neither the speed of reconfiguration nor the data loss due to a reconfiguration is a serious drawback [21]. This motivates the study of array interconnection as the basic architecture for a 2-D MEMS optical switch.

In Section II, we explore the switching capability of the rectangular array and derive two routing control algorithms for this in Section III, optimizing different objectives. The performance of the routing control algorithms is then quantified in Section IV. In Section V, we further discuss various issues concerning the implementation of a 2-D MEMS optical switch using a rectangular array.

II. Switching Capability

A (m, n) rectangular array interconnection has $m+n$ inputs $I_1, I_2, \ldots, I_{m+n}$ and $m+n$ outputs $O_1, O_2, \ldots, O_{m+n}$, as shown in Fig. 3. It consists of mn 2×2 switches. A *permutation* of the inputs into the outputs specifies a connection pattern between the inputs and the outputs, e.g., $\binom{2413}{1234}$ represents the connection pattern with input–output pairs $\{I_2, O_1\}$, $\{I_4, O_2\}$, $\{I_1, O_3\}$, and $\{I_3, O_4\}$. We then need to know the kind of permutations that may be realized by setting the 2×2 elements in the interconnection. The structure of the 2×2 switch itself implies that a beam can only propagate along the direction indicated by the arrows in Fig. 3. Therefore, not all connections will be possible in the array.

Definition 1: A connection $\{I_x, O_y\}$ is allowable if a directed path from the input to the output exists, such that $\max(1, m-x+1) \le y \le \min(m+n, 2m+n+1-x)$.

Definition 2: An allowable permutation is one that has only allowable connections.

According to the definition, the connection $\{I_{m+3}, O_{m+2}\}$ in Fig. 3 is allowable, since there exists a directed path from the input to the output, as shown; on the other hand, the connection $\{I_{m+2}, O_{m+n}\}$ is not allowable. The following theorem will then determine the switching capability of this array interconnection.

Theorem I: Any allowable permutation can be realized in an (m, n) array interconnection.

Proof: Starting with the first row, consider first the case where output O_1 is to be connected to input I_m. All switches in the first row are set to "cross." Otherwise, assume that in the permutation to be realized, output O_1 is to be connected to input $I_{m+k} (1 \le k \le n)$. This connection can be established by setting the switches linked to $I_{m+k}, I_{m+k+1}, \ldots, I_{m+n}$ as shown in Fig. 3. Next, the remaining switches in the $(1, k-1)$ subarray can be set as follows.

The leftmost switch in the $(1, k-1)$ subarray is first examined. There are two inputs attached to it, namely the left input and the top input, as depicted in Fig. 3. It is then configured according to the following rules.

1) If the output connected to the left input is on the same column, set the switch to "bend."
2) If the output connected to the top input is on the same column, set the switch to "cross."
3) Otherwise, the switch can be set to either state.

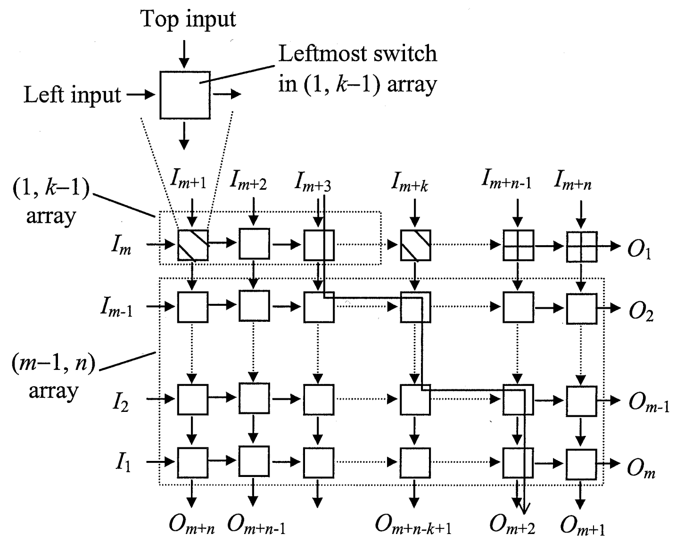


Fig. 3. Rectangular array.

After setting the leftmost switch, we have the remaining unset switches in a $(1, k-2)$ subarray, which can then be configured recursively following rules 1–3. Rules 1 and 2 guarantee that the connections remain allowable as it appears to the resulting $(m-1, n)$ array after setting the switches in the first row. Therefore, the assertion in Theorem 1 for (m, n) array will be true if it is true for the $(m-1, n)$ array. We complete the proof by noting that setting a $(1, n)$ array in the same way as setting the $(1, k-1)$ subarray in the above will realize the given permutation to the $(1, n)$ array. Theorem 1 then follows by induction. □

This procedure also suggests the routing control needed to realize any permutation. However, the routing of a permutation may not be unique due to the arbitrary choice in rule 3 of this proof. Note that if the switches are preconfigured to realize a permutation, removing some of the existing connections to realize a new permutation may be necessary, but this should be acceptable for most circuit-switched WDM networks of the type mentioned in Section I.

III. Routing Control

Two routing strategies are discussed, namely the most-bend (MB) and the least-bend (LB) strategies. As the names imply, the MB strategy maximizes the number of switches in the "bend" state, while the LB strategy takes the opposite approach. Rule 3 in the proof of Theorem 1 is modified as follows for MB and LB.

MB Strategy

3) Otherwise, set the switch to "bend."

LB Strategy

3) Otherwise, set the switch to "cross."

In the following, we introduce two array variables $s = [s(1) \ldots s(m+n)]$ and $d = [d(1) \ldots d(m+n)]$ for convenience in describing the algorithms, where

$s(x)$ input (source) connected to output $O_x \in \{1, \ldots, m+n\}$

$d(x)$ output (destination) connected to input $I_x \in \{1, \ldots, m+n\}$

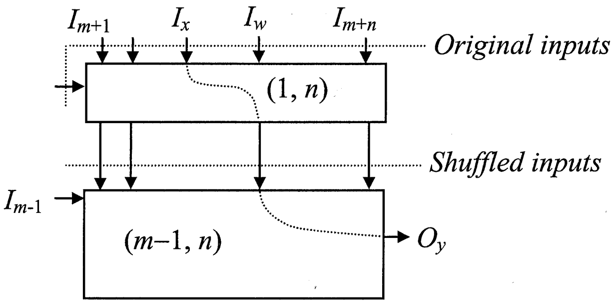


Fig. 4. Input shuffing.

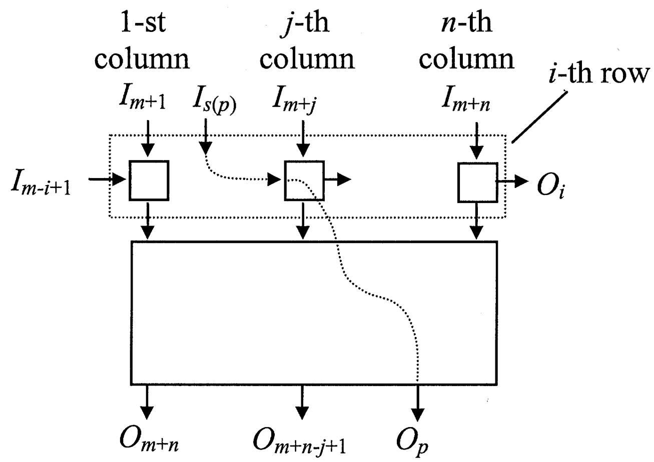


Fig. 5. Definition of p for switch at (i, j).

with $x \in \{1, \ldots, m+n\}$ and the relation $s[d(x)] = x$ and $d[s(x)] = x$. The variables s, d essentially define the permutation of the inputs into the outputs. As in the proof of Theorem 1, setting the first row of an (m, n) array changes the permutation of the inputs and the outputs as it appears to the next row, as shown in Fig. 4, specifically $s(y) = x$ in the original permutation, but $s(y) = w$ as it appears to the second row. As such, both s and d need to be updated in each iteration.

Consider a switch at the (i, j) position (on the ith row and the jth column) in the "cross" state and let p denote the output connected to its left input, as shown in Fig. 5. After setting the switch to "bend" state, s and d appear different to the next row, and p also changes as it appears to the next switch at $(i+1, j)$. It is clear that, on the other hand, a "cross" state will not change s, d, and p. When the switch at (i, j) is set to "bend," the necessary updates are included in the following subroutine:

```
bend(i, j)
  set switch at (i, j) to "bend"
  s(p) ← m + j
  swap (p, d(m + j))
end.
```

In the following, the inputs and outputs of a single switch or an array of switches are simply described as *left*, *right*, *top*, and *bottom* depending on the side to which they are attached. Furthermore, when setting the switches on the ith row, if the right output of the ith row is connected to the top input of the switch at (i, k), the kth column is referred to as the *delimiting column*, and the switches from $(i, 1)$ to $(i, k-1)$ form the *residual subarray* of the ith row. Assuming all switches are in the "cross" state initially, the MB and the LB algorithms are readily given by the following pseudocodes (comments are in bold).

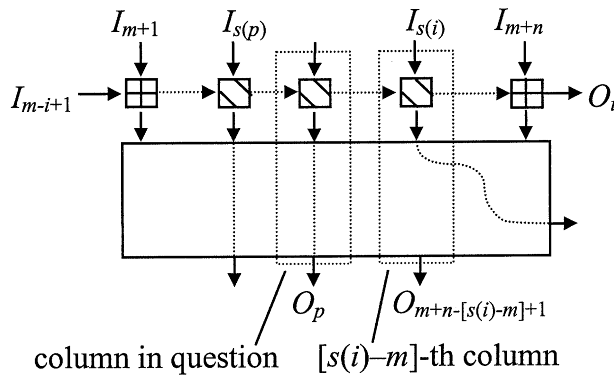


Fig. 6. Setting of the ith row in LB algorithm.

```
MB Algorithm
do for each row
for i = 1 to m
  true if left input not connected to
  right output of the ith row
  if s(i) ≠ m − i + 1 then
    p ← d(m − i + 1)
  do for each top input of the residual
  subarray of the ith row
  for j = m + 1 to s(i)
    true if top input of switch (i, j − m)
    not connected to bottom output of the
    (j − m)th column
    if d(j) ≠ m+n−(j−m)+1 then bend (i, j−m)
    end for
  end if
end for
```

When searching through the columns along the ith row, LB algorithm follows a faster procedure. The LB algorithm checks for the cases where the output connected to the left input is at the left side of the delimiting column, i.e., O_p is to the left of $O_{m+n-[s(i)-m]+1}$ (as depicted in Fig. 6), instead of scanning through every columns of the ith row.

```
LB Algorithm
do for each row
for i = 1 to m
  true if left input not connected to
  right output of the ith row
  if s(i) ≠ m − i + 1 then
    p ← d(m − i + 1)
    true if the output connected to left
    input, O_p, is at the left side of the
    delimiting column
  while p > m + n − (s(i) − m) + 1
      the output connected to left input,
      O_p, is at the (m + n − p + 1)th column
```

```
      bend (i, m + n − p + 1)
    end while
    s(i) − m is the delimiting column
    bend (i, s(i) − m)
  end if
end for
```

IV. Number of Bends

In an MEMS-based array interconnection, a "bend" state is achieved by a reflection. A light beam loses power as it is reflected due to the imperfect mirror surface [1], [12]. On the other hand, angular variation of the mirror (causing the incident angle of the light beam to divert from 45°) adds to the power loss that results from reflection. Therefore, the "cross" state may be more favorable than the "bend" state. This is an example where the performance of the optical switch is state-dependent. The settings of the array interconnection that result from the MB and LB routing controls represent two extreme cases that gives the maximal and minimal number of switches in "bend" state respectively. The analysis on the "number of bends" involved in the LB and MB routing controls is given in this section. In the following, we derive the number of permutations that can be realized while maintaining a given number of bends in the interconnection. This will lead to the derivation of the distribution of the number of permutations realized over the number of bends. We first provide the following definitions:

$Z_{i,j}(b)$ number of permutations realized in an (i, j) array with b bends

$Z_{i,j}(b, b_1)$ number of permutations realized in an (i, j) array with b bends, b_1 of which are on row 1.

Clearly $Z_{i,j}(b)$ can be obtained from $Z_{i,j}(b, b_1)$ by summing over various values of b_1, which varies from 0 to b or n, whichever is smaller. The remaining $b - b_1$ bends will then reside in the $(i - 1, j)$ array, thus establishing the recursive relation

$$Z_{i,j}(b) = \sum_{b_1=0}^{\min(b,j)} Z_{i,j}(b, b_1) \tag{1}$$

where $Z_{i,j}(b, 0) = Z_{i-1,j}(b)$. We observe that there is exactly one permutation that can be realized without any bend in the array of any size. In addition, we cannot have any bend if the array has zero row or column. This gives the boundary values as

$$\begin{aligned} Z_{i,j}(0) &= 1, \ 0 \le i \le m, 0 \le j \le n \\ Z_{i,0}(b) &= 0, \ 0 \le i \le m, b > 0 \\ Z_{0,j}(b) &= 0, \ 0 \le j \le n, b > 0. \end{aligned}$$

The exact form of the recursive relation depends on the strategy (i.e., LB or MB strategy) with which the switches are set. This is discussed in the following subsections.

A. LB Routing

With the exception of the rightmost bend that connects an input to row 1 to output O_1 (referring to Fig. 7), a bend at row 1 implies that all other switches on the same column are set to "cross." This effectively eliminates one column from the array. Following this, $b_1 - 1$ columns $(b_1 > 0)$ will therefore be eliminated if b_1 switches in row 1 are to be set to "bend." If there are b switches to be set to "bend," the remaining $b - b_1$ bends are located in the resultant $(i-1, j-b_1+1)$ array. On the other hand, there are $\binom{j}{b_1}$ ways to choose b_1 switches from the j switches of row 1. We therefore obtain

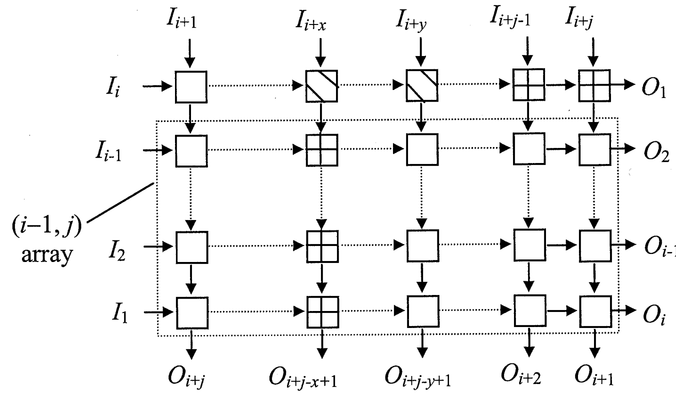


Fig. 7. Elimination of column.

$$Z_{i,j}(b, b_1) = \binom{j}{b_1} Z_{i-1,j-b_1+1}(b - b_1), \ 1 \le b_1 \le n \tag{2}$$

where $\binom{j}{b_1} = (j!)/(b_1!(j - b_1)!)$ is the binomial coefficient.

Next, we will find the upper limit of b. Assume that in an (i, j) array, there are r rows with nonzero number of bends, namely $b_1, b_2, \ldots, b_r$, we can treat the array as consisting of r rows (rows without bends can be ignored). After setting the first row, $j - b_1 + 1$ columns remain, as explained in the argument leading to (2). However, we must have $b_2 \le j - b_1 + 1$ to continue, or $b_1 + b_2 \le j + 1$. Proceeding with the similar reasoning, we have in general

$$b = \sum_{i=1}^{r} b_i \le j + r - 1 \le j + i - 1.$$

With LB routing, there are at most $i + j - 1$ bends in an (i, j) array.

B. MB Routing

As opposed to the LB routing, a "cross" to the left of the rightmost bend of row 1 implies that all the switches on the same column are set to "cross." These columns are eliminated from the array. However, the number of columns eliminated depends on the position of the rightmost bend. Let k be the column on which the rightmost bend of row 1 locates, and let b_1 be the number of switches in row 1 in "bend" state. The resultant $(i-1, j - k + b_1)$ array contains the remaining $b - b_1$ bends, where b is again the number of switches set to "bend" state in the entire interconnection. Given column k, where the rightmost of the b_1 bends is located, there are $\binom{k-1}{b_1-1}$ ways to choose the positions of the remaining $b_1 - 1$ switches on row 1. Therefore

$$Z_{i,j}(b, b_1) = \sum_{k=b_1}^{j} \binom{k-1}{b_1-1} Z_{i-1,j-k+b_1}(b - b_1), \ 1 \le b_1 \le j. \tag{3}$$

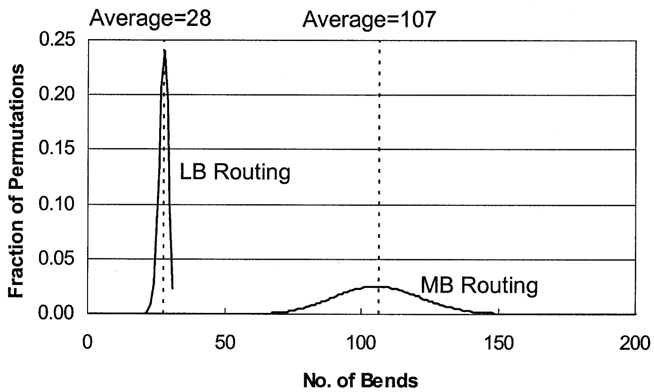


Fig. 8. Performance of routing algorithms.

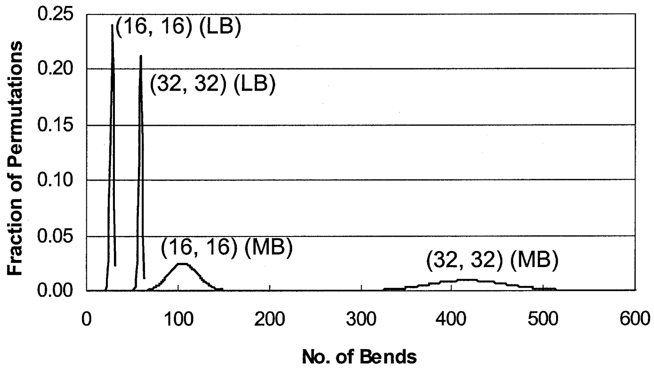


Fig. 9. Comparison of (16, 16) and (32, 32) array.

C. Results

Substituting (2) for LB routing and (3) for MB Routing in (1), we obtain the recursive formula for calculating $Z_{i,j}(b)$. The normalized distribution $Z_{i,j}(b)/\sum_b Z_{i,j}(b)$, or the fraction of permutations for LB and MB routing, is plotted in Fig. 8, assuming a (16, 16) array. The difference is undoubtedly large, which means that the effect of minimizing the number of bends is significant. While the bends represent power loss through the array interconnection, this results in a less stringent power budget or better signal quality. The performance of any other routing strategy is bounded between these two. The vertical dotted lines gives the averages for the two graphs, which fall at 28 and 107, respectively. Although not clear from the figure, the number of bends for LB routing is limited to 31, while it spans over the range of 0 to 256 for MB routing.

The (16, 16) and (32, 32) arrays are compared in Fig. 9. The effect of optimizing the number of bends is quite similar in both arrays. The average number of bends in a (32, 32) array is 59 and 419, respectively, as compared with 28 and 107 in the (16, 16) array. Larger deviation from the average of the distribution can be observed in the array with larger size, especially with the MB routing. On the other hand, Fig. 10 shows the plots of the average number of bends against the array size. A rapid growth in the average number of bends occurs when the MB routing is applied, while it increases mildly with LB routing. This results in a larger difference in performance between the two routing strategies when the array size grows. This is reasonable because the LB and MB routing give a maximum number of bends that grow as $o(n)$ and $o(n^2)$, respectively.

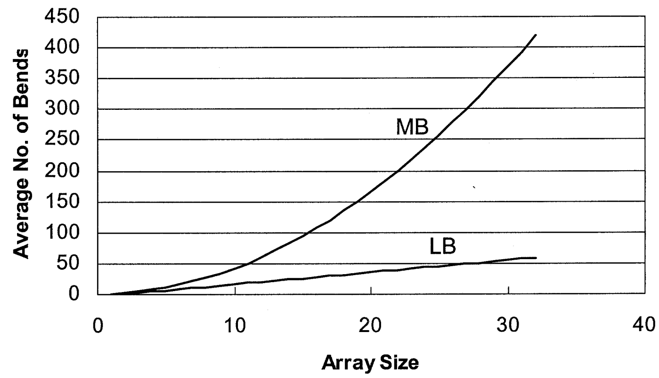


Fig. 10. Average number of bends versus array size.

V. Discussion

A. Decomposition of an (n, n) Array Into Two Independent Rearrangeable Switches

It has been proposed in [12] that by using two-sided mirrors, an (n, n) array interconnection can be used to realize two permutations of n inputs into n outputs with connection symmetry. This means that if input i is to be connected to output j in one permutation, then input j should be connected to output i in the other permutation. By exploring the connection capability of the array interconnection in the previous section, an (n, n) array can also be used as two independent rearrangeable switches where the two permutations realized by the two switches can be independent (not necessarily symmetrical). Note that this is possible only if the individual connections are allowed to be "bent" more than once. Although the two switches are not strictly nonblocking, as in the operation mode proposed in [12], rearrangeability may suffice for practical applications, as pointed out previously.

Corollary 1: Any connection pattern with the restriction that the inputs at the top are connected only to the outputs at the right, and the inputs at the left are connected only to the outputs at the bottom can be realized in the rectangular array of Fig. 3.

Proof: Obviously, any connection pattern satisfying the above restriction is allowable in the sense of Definition 1. The corollary then follows from Theorem 1. □

B. Optimization of Individual Signals

It has been pointed out that a "bend" state causes power loss of the signal beam in the MEMS-based array interconnection. The proposed MB and LB routing controls result in two extreme cases that have the maximal and minimal, respectively, number of switches in "bend" state. However, there are occasions where we are concerned more about the power loss of the individual signals than the total power loss caused by all the mirrors in "bend" state. Although the LB routing will minimize the overall number of bends in the interconnection, it may not always minimize the number of bends experienced by the individual signals that are "bent" the most number of times, as illustrated in Fig. 11. Clearly, I_5-O_6 is the signal path that is "bent" the most number of times (7 bends). If we reverse the state of the switch at (3, 3) and (5, 5) (shaded in gray), the permutation and the overall number of bends remain the same, and the signal path I_5-O_6 remains to be "bent" the most times, but with less

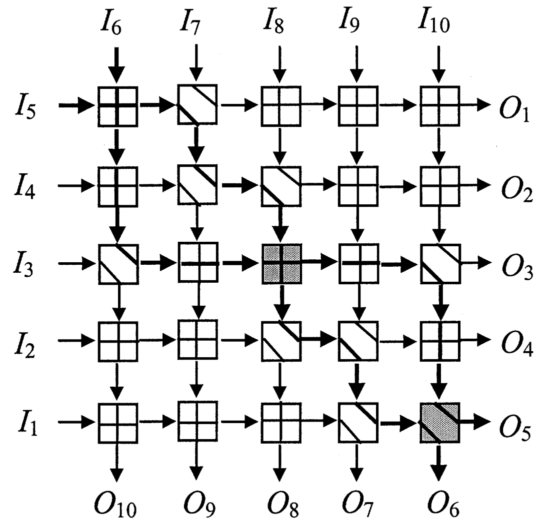


Fig. 11. Number of bends of individual signals.

number of bends (5 bends). However, this optimization is more complex, since the decision made in an iteration must take into account the decisions made in the previous or later iterations and may not be achieved with simple recursive algorithms such as the MB and LB algorithms.

C. Rearrangeable Switch Based on Array Interconnection

We examine next the minimum number of switches needed to realize all connection patterns that involve only the inputs at the top and the outputs at the right. Given any such connection pattern, we have to route all the connections, making use of as few switches as possible. Starting with the settings of switches on the first row, as shown in Fig. 3 (the other switches are arbitrarily set), the (m, n) array is reduced to a $(m-1, n-1)$ subarray, also with a connection pattern that involves only the top inputs and the right outputs. Proceeding similarly, all the switches will be set recursively, guaranteeing that the minimum number of switches are used. Eliminating the unused switches and the switches with a fixed setting, e.g., switches at (i, i), we obtain the reduced array architecture that can realize any connection pattern with n inputs and m outputs, as shown in Fig. 12. The number of switches N is given by

$$N = mn - \frac{m(m+1)}{2}.$$

Although the (m, n) array interconnection can realize any allowable connection pattern between its $(m+n)$ inputs and $(m+n)$ outputs, it may not be very useful as a switching network in practice because not all connection patterns can be supported. Given a connection pattern, however, we can shuffle the inputs appropriately so that the resulting connection pattern appears to be allowable to the array interconnection. This gives a rearrangeable architecture that can realize any permutation of the $(m+n)$ inputs and $(m+n)$ outputs, as shown in Fig. 13(a). The shuffler networks can also be implemented with array interconnection, and this gives rise to a rearrangeable architecture with $(m+n)$ inputs and $(m+n)$ outputs constructed completely with array interconnection, e.g., the architecture shown in Fig. 13(b), with the number of switches N given by

$$N = \frac{(m+n)(m+n-1)}{2}.$$

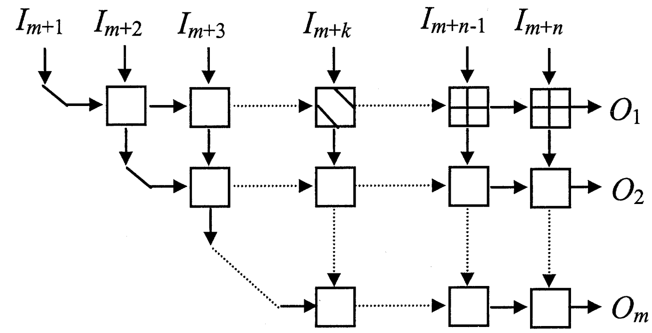
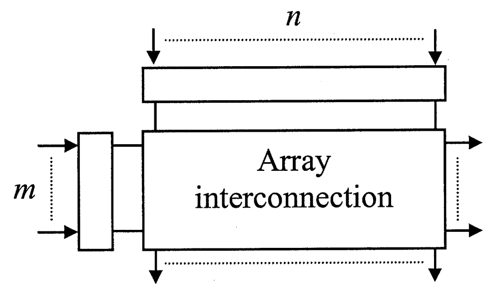
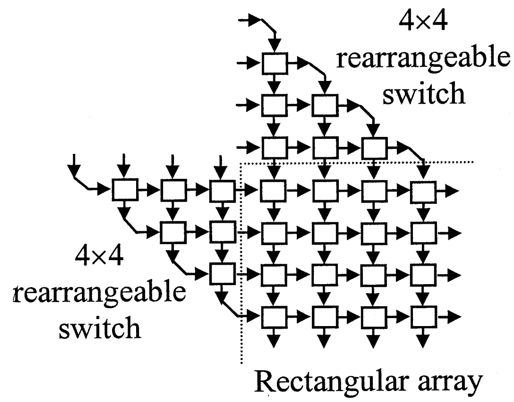


Fig. 12. Rearrangeable switch with n inputs and m outputs.



(a)



(b)

Fig. 13. $(m+n) \times (m+n)$ rearrangeable switch.

VI. CONCLUSION

In this paper, the rectangular array interconnection suitable for constructing MEMS-based optical switch is considered. The switching capability of the interconnection is studied. This has led to the proposal of two routing controls that optimize the number of switches in the "bend" state, by either minimizing or maximizing it. We further derive the methods for calculating the number of permutations that can be realized with a given number of bends in the array. Understanding of the switching capability of the rectangular array allows us to study the construction of rearrangeable optical switches based on the array interconnection with an equal or unequal number of inputs and outputs.

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