Micromachined L-Switching Matrix

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***Abstract*-Explosion in Internet applications has stimulated active research activities in expanding the capability of the current telecommunication networks. These activities include implementing faster electronics to process the higher data bit rates, or developing Wavelength Division Multiplexing (WDM) techniques, and novel optical networks components to increase the information carrying capacity of the optical networks. As the data bit rates increases, it will become increasingly difficult to implement an electronic switching fabric solution. It is known that the information carrying laser beams should be dealt with at the optical level. One of most promising optical network components is micromachined optical cross connect switches. In this paper, we present a new crossbar switching design methodology that decreases the number of mirrors and electrodes needed while maintaining same non-blocking port switching capability. More importantly, this new architecture also reduces the distance of free-space propagation of light beams, thus reducing the loss due to guassian-beam divergence during free-space propagation of light.**

I. INTRODUCTION

Optical fiber offers many advantages over traditional electric cables, including high bandwidth, low-loss, lightweight, immunity from electromagnetic interference, and the ability to increase the network capacity by wavelength division multiplexing (WDM). The significant demand for faster and higher capacity means of transferring data over the Internet and Local Area Network has prompted significant growth of the optical fiber networks. Stimulated by the current demand for the need of optical network, intensive research in universities and companies is performed for building low-cost, reliable and scalable optical components such as optical switches.

In the past, Microelectromechanical systems (MEMS) optical switches have demonstrated to have superior optical performance when compared to competing solid-waveguide switches. MEMS-based switches have been able to achieve low insertion losses, low crosstalk and low polarization and wavelength dependent. Past designs of 2×2 MEMS-based switches have shown the advantages of MEMS technology [1][2][3]. However, these designs do not address the scalability issues of 2-dimensional (2D) MEMS switches in today's optical network. Larger N×N optical switches matrixes have also been demonstrated [4][5]. These designs are scalable to larger input/output ports, but issues such as substantial difference in optical path lengths for the longest and the shortest paths, which result in uneven losses among output ports, have not been fully addressed [6]. In this paper, we present a L-switching matrix, which decreases the longest path length by 25%, and shortens the difference between the longest and shortest path lengths by 50%. By interconnecting a number of smaller L-switching matrixes into a multistage interconnection network such as Clos network, 64×64 optical switches can be realized with comparable losses as a 32×32 optical switches interconnected from conventional crossbar switches.

II. 4×4 L-SWITCHING MATRIX ARCHITECTURE

To accommodate N×N ports, L-switching matrix utilizes $\frac{N^2}{4}$ double-sided and $\frac{2N^2}{4}$ single-sided mirrors for total of $\frac{3N^2}{4}$ mirror and counter-electrodes. The overall design architecture of a 4×4 L-switching matrix is shown in Fig. 1. The double-sided mirrors are placed in a square format two sides of which are surrounded by the input ports. The double-sided mirrors redirect lights into the their destination quadrant (I or II). Each quadrant consists of $\frac{N}{2}$ output ports and contains $\frac{N^2}{4}$ single-sided mirrors. The single-sided mirrors redirect lights to the correct destination ports. A set O represents the output ports. The set O is divided into two subsets, namely O_1 and O_2 depending on the origins of the optical signals. Optical signals in O_1 originated from I_1 and O_2 from I_2. I_1 are input optical signals that are parallel to x-axis, where I_2 are those parallel to the y-axis. I_1 and I_2 are further divided into smaller subsets according to their corresponding O_1 and O_2.

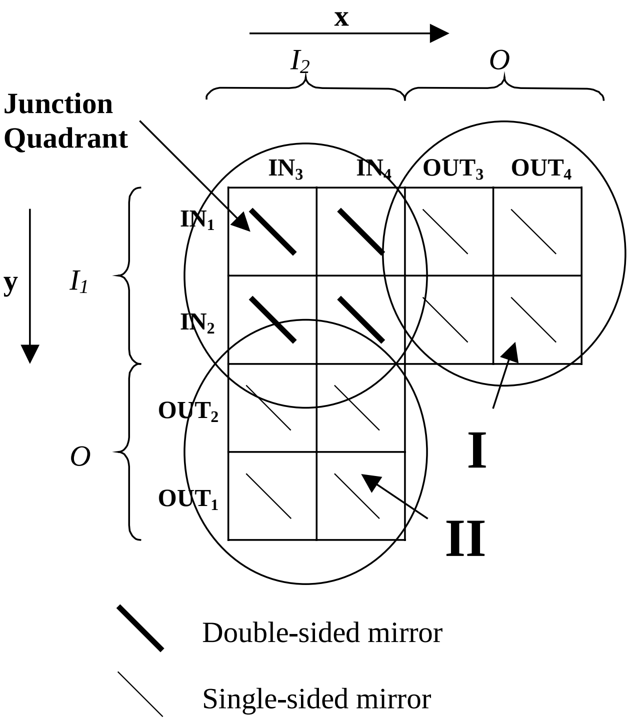


Fig. 1. Design architecture of L-switching matrix.

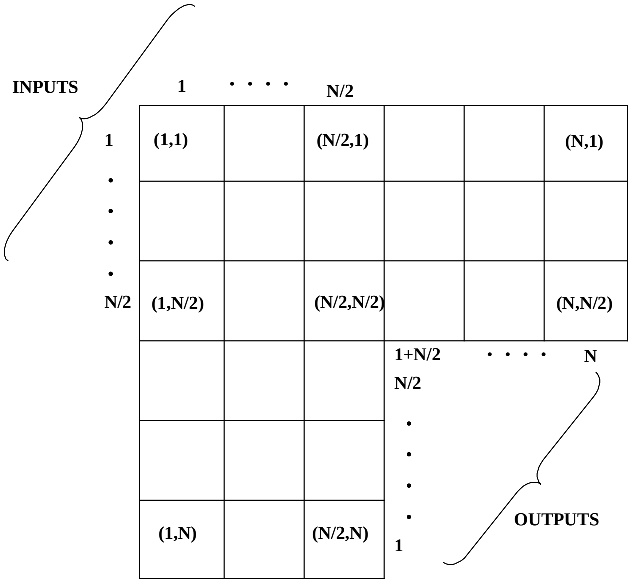


Fig. 2. Coordinate system of an N×N L-switching matrix.

$$\begin{array}{lll} I_1' & \textit{when} & (O_1 - 1) < \left(\frac{N}{2}\right) \\ I_1'' & & \textit{otherwise} \\ I_2' & \textit{when} & (O_2 - 1) \geq \left(\frac{N}{2}\right) \\ I_2'' & & \textit{otherwise} \end{array}$$

where

$$I_1' \cap I_1'' = 0; \qquad I_1' \cup I_1'' = I_1$$

$$O_1' \cap O_1'' = 0; \qquad O_1' \cup O_1'' = O_1$$

and

$$I_2' \cap I_2'' = 0; \qquad I_2' \cup I_2'' = I_2$$

$$O_2' \cap O_2'' = 0; \qquad O_2' \cup O_2'' = O_2$$

The coordinate system used to define the positions of micro-mirrors is illustrated in Fig. 2.

The coordinates of the micro-mirrors to reflect light beams from I_1' and I_2' are

Junction Quadrant

$x = I_2'; \qquad y = I_1'$

Quadrant I

$x = O_2'; \qquad y = I_1'$

Quadrant II

$x = I_2'; \qquad y = N - O_1' + 1$

The coordinates of the micro-mirrors to reflect light beams from I_1'' and I_2'' are

Quadrant I

$x = O_1''; \qquad y = I_1''$

Quadrant II

$x = I_2''; \qquad y = N - O_2'' + 1$

The operating principle of a 4×4 L-switching matrix is illustrated in Fig. 3. Each colour in Fig. 3 represents light beam from each input optical fibre. As shown, by turning predetermined combinations of micro-mirrors on and off, non-blocking port-to-port network can be achieved.

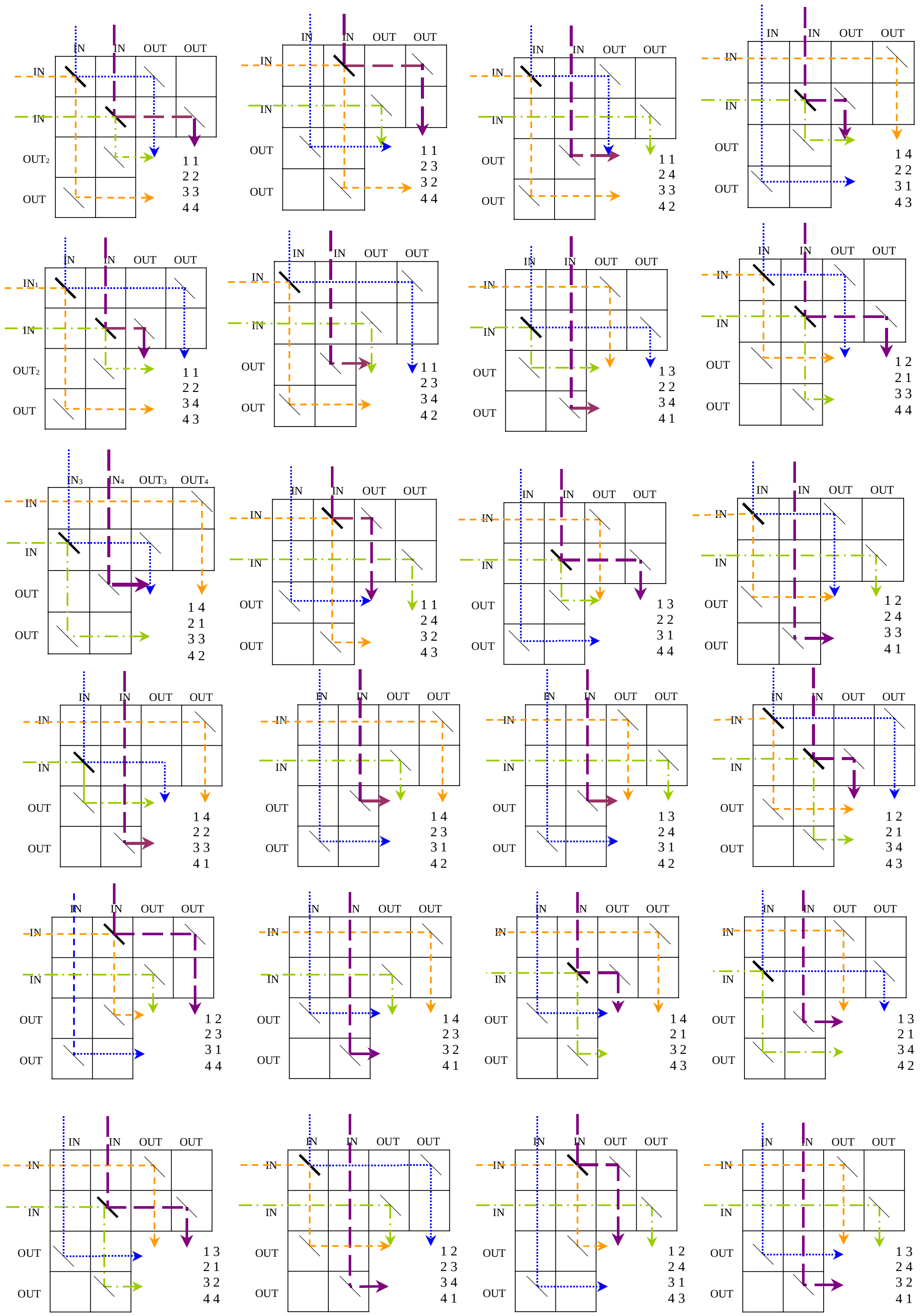


Fig. 3. 4×4 L-switching matrix operation principle.

III. PERFORMANCE ISSUES

It is understood that the beam-divergence is one of the dominant factor in limiting the number of input/output ports in a 2D micromachined optical switch design [7]. Therefore, it is important to minimize the free-space propagation of optical beam so as to reduce the effect of beam divergence. The current crossbar switching illustrated in Fig. 4(a) has a most distance path of *2N-1* and a least distance path of 1. On the other hand, L-switching matrix illustrated in Fig. 4(b) has a most distance (MDP) and least distance path (LDP) of $N+\left(\frac{N}{2}-1\right)$ and $\left(\frac{N}{2}+1\right)$.

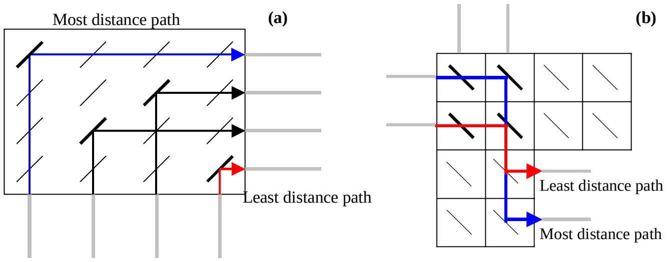


Fig. 4. Most distance and least distance path of Conventional Crossbar switch (a) and L-switching matrix.

Fig. 5 shows a comparison of the MDP as a function of port-count. It is observed that L-switching matrix shortens the MDP by 25% when compared to the conventional crossbar switches. However, one of the major obstacles of 2D MEMS optical switches, which remain unresolved, is the non-uniformity of losses among output ports [6][7]. The substantial difference losses limits the current 2D MEMS switches port-count to 32×32. The number of pitches is defined as the number of mirror pit that the optical beam passes through.

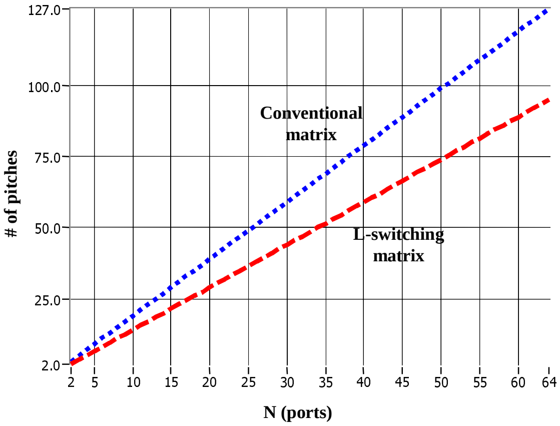


Fig. 5. Most distant path comparison between conventional crossbar switches (blue) and L-switching matrix (red).

Fig. 6 shows the path difference comparison between L-switching matrix and convention crossbar switches. It is projected that with the new design, the inter-port losses uniformity improves by 50%. In other words, L-switching matrix can be expanded to port-count of 64×64 while maintain the same difference in losses experience by a 32×32 conventional crossbar switch.

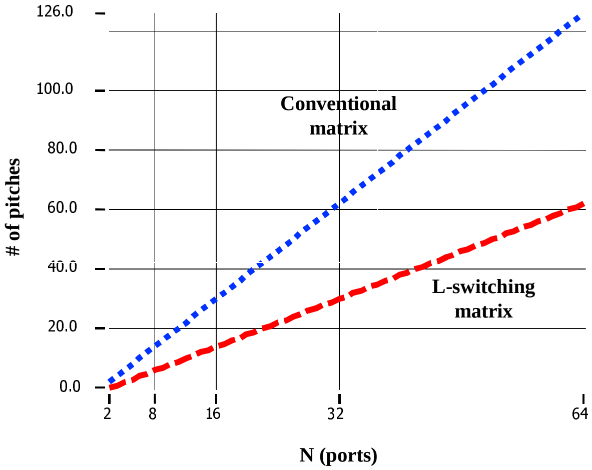


Fig. 6. Path difference comparison between conventional crossbar switches (blue) and L-switching matrix (red).

An alternative approach to increasing port-count is to interconnect smaller 2D MEMS switches submodules to form multistage interconnection network. These designs typically have high loss and poor loss uniformities across all output ports. An example of interconnecting small switch submodules into a three-stage Clos network is illustrated in Fig. 7. An N×N OXC is implemented using m×m switching submodules.

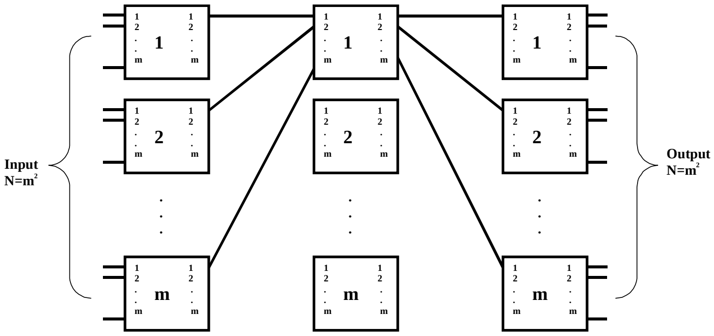


Fig. 7. Clos network implemented using smaller switching submodules.

The most distance paths of the Clos network using L-switching matrix and conventional crossbar switch are

$3(\frac{3}{2}\sqrt{N}-1)$ and $3(2\sqrt{N}-1)$. The comparison is illustrated in Fig. 8 shows that the most distance path of a 64×64 Clos network when using L-switching matrix as submodules is comparable in to that of a 32×32 conventional crossbar Clos network.

The performance of L-switching when interconnected into a Clos network reveals superior performance when the difference in most distance path and least distance path is analyzed. The relative insertion loss of Clos network using L-switching matrix and conventional crossbar switch is shown in Fig. 9. Fig. 10 shows the percentage reduction in relative insertion loss between the two submodule designs. A theoretical reduction of 57% in insertion loss is achievable, when port-count is 64×64, using L-switching matrix.

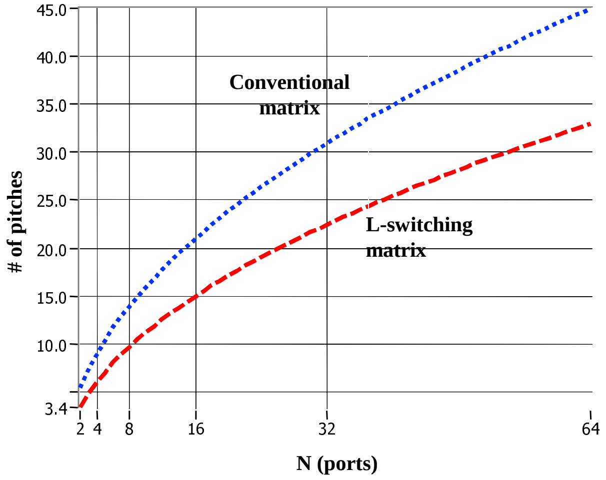


Fig. 8. Difference in overall most distant path comparison of Clos switch using conventional crossbar switches (blue) and L-switching matrix as unit switching modules (red).

The ratio of the power carried within a micro-mirror of radius ρ_o in the transverse plane at position z to the total power is [8]:

$$\frac{P_{mirror}}{P_{total}} = 1 - e^{\left[-\frac{2\rho_o^2}{W^2(z)}\right]} \qquad (1)$$

where

$$W(z) = W_o\left[1+\left(\frac{z}{z_o}\right)^2\right]^{\frac{1}{2}} \qquad (2)$$

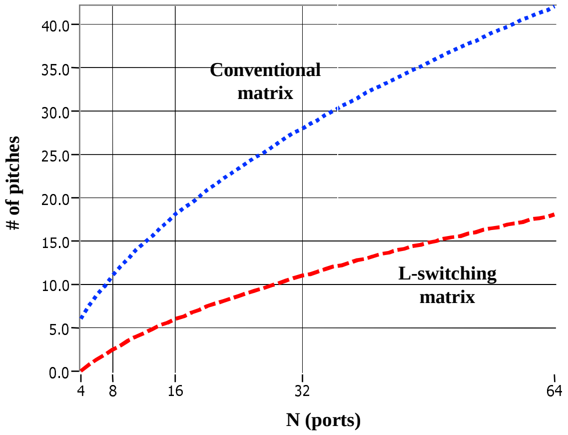


Fig. 9. Difference between the longest and shortest path lengths of Clos network using conventional crossbar switches (blue) and L-switching matrix as unit switching modules (red).

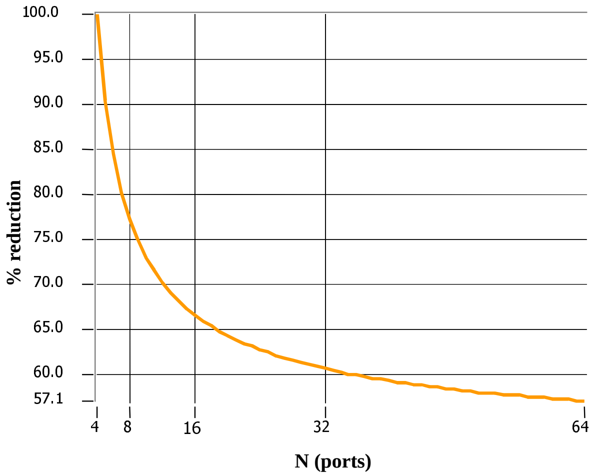


Fig. 10. Percentage reduction of difference between the longest and shortest path lengths of Clos network when L-switching matrix is used as unit switching modules.

It is assumed the minimum beam waist, W_o, occurs when z = 0. The beam radius increases gradually with z, reaching $\sqrt{2}W_o$ at z = z_o. z_o is defined as

$$z_o = \frac{2\pi W_o^2}{\lambda} \qquad (3)$$

In the analysis, ρ_o is designed to be 200µm and is 1.5 times that of W_o. λ is assumed to be 1.55µm. Fig. 11 shows the ratio of power received by the mirror to the total power. It is shown that the MDP of the L-switching matrix is retains considerably larger power than its conventional crossbar switches. The superior optical performance is shown in Fig. 12. For N= 6, the difference in power of the MDP and LDP of the L-switching matrix is 25% and that of conventional crossbar switches is close to 50%.

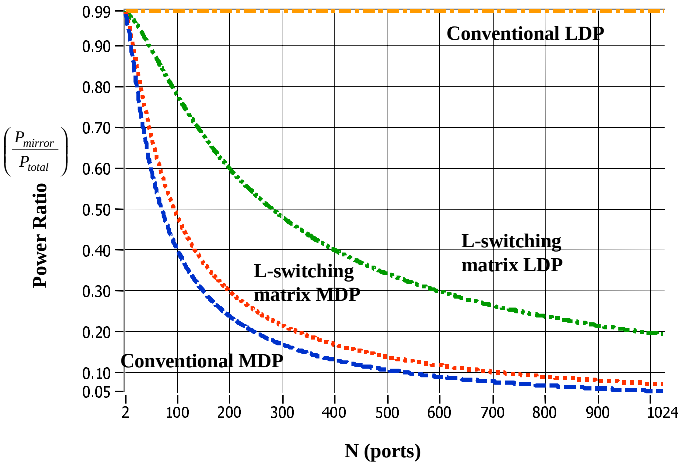


Fig. 11. Ratio of the power carried within the last mirror of the most distance path in the transverse plane to the total power.

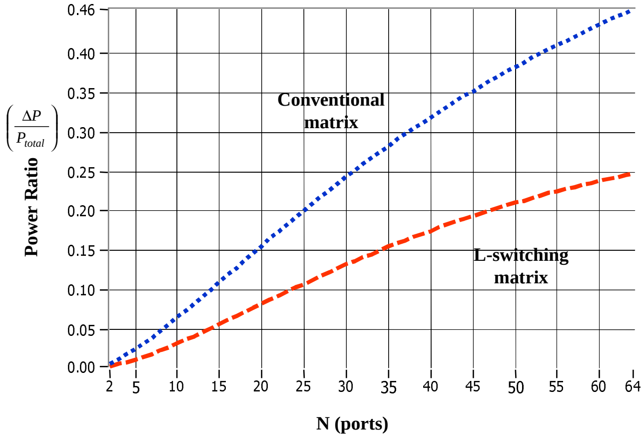


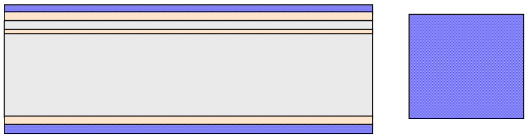
Fig. 12. Ratio of the power difference in the MDP and LDP within the last mirror of the most distance path in the transverse plane to the total power.

One of the major concerns of network equipment carriers is the serviceability of a MEMS optical switch. In the convention cross-bar configuration, each input to each output as an unique path. Failure of a micro-mirror would require replacement of the entire optical switch. L-switching matrix, on the other hand, has incorporated redundancies in its input to output light paths. Each input to each output has N/2 solutions. These redundancies greatly increase the serviceability of 2D MEMS optical switches.

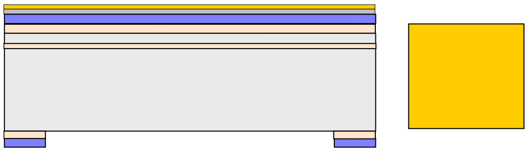
IV. FABRICATION PROCESS

1. <100> Silicon-On-Insulator (SOI) with 20um device layer silicon, 2um buried oxide layer, 505um handle Si layer.

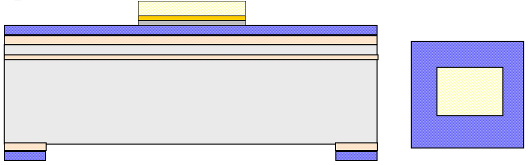
2. Deposit and pattern 0.7µm low stress silicon nitride as torsion bar and 0.3um SiO_2 as insulation layer on top and bottom of SOI.



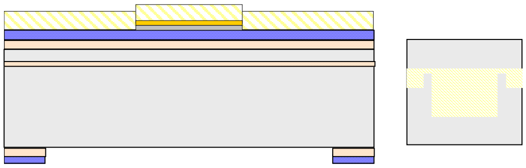
3. Deposit Au (0.2µm) and Cr (0.2µm) metal layers by vacuum evaporation and pattern bottom of SOI.



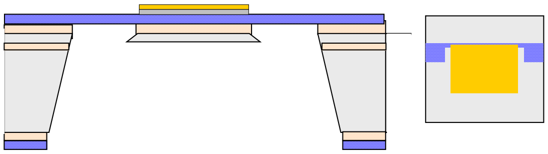
4. Strip Au and Cr to pattern mirror area.



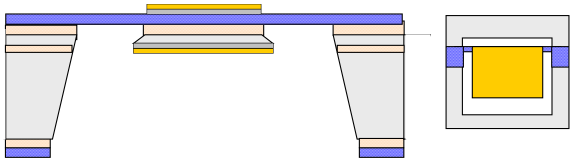
5. Pattern torsion bar and strip nitride and oxide.



6. Etch handle Si layer with KOH from underneath to release mirror.



7. Deposit metal from underneath to from double-sided mirror.



V. CONCLUSION

An improved micromachined L-switching matrix has been proposed for use as optical cross-connect switches in core-transport lightwave networks. This novel architecture not only provides superior optical performance in terms of insertion loss over convention cross-bar configuration, it also provides inherent light-path redundancies to bypass failed micro-mirrors. Theoretically, L-switching matrix can be scaled to 64×64 port-count. With L-switching matrix, 2D MEMS optical switches are no longer restricted by the commonly acknowledged maximum of 32×32.

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