

## High-density Connection-symmetric Free-space Micromachined Polygon Optical Crossconnects with Low Loss for WDM Networks

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Optical crossconnects (OXC) with large port count appear to be emerging as critical elements for provisioning and restoration in future WDM networks [1]. In the face of swiftly rising demand, the chief challenge facing them is port count. As port count soars, achieving low loss and low crosstalk become challenging tasks for all photonic switching technologies. Moreover, the physical size and complexity of the switch fabric tend to scale rapidly with port count, quickly reaching practical limits. In this paper, we propose high-density micromachined *polygon* OXCs utilizing network-connection symmetry. The approach significantly reduces the physical size of the switch fabric and simplifies its management. A  $16 \times 16$  (8 bi-directional) switch with low insertion loss (3.1~3.5 dB) for nodal degree 2 and a  $12 \times 12$  (6 bi-directional) hexagon switch for nodal degree 3 on  $1 \text{ cm} \times 1 \text{ cm}$  silicon chips have been experimentally demonstrated. The results suggest the practicality of OXC with far higher port count than previously anticipated.

Due to the connection-symmetry inherent in current core-transport networks, OXC deployed in such networks will also be connection-symmetric. This is illustrated in Fig. 1 for an OXC of nodal degree 2. Since all supported connections are bi-directionally symmetric, all switching is done in latched pairs. This is a feature whose substantial lurking economics can be naturally incorporated into a free-space OXC like the  $4 \times 4$  device we demonstrated recently [2]. By reflecting signals in symmetric pairs from the two sides of free-rotating micro-mirrors, symmetric connections can be supported. Figure 2(a) illustrates this for a matrix switch of nodal degree two; here, the size and complexity of a  $16 \times 16$  switch fabric is essentially reduced to that of an  $8 \times 8$  conventional matrix switch. For higher nodal degree, optical *polygon* switches are required to avoid blocking. Figure 2(b) shows an optical hexagon switch for nodal degree 3. When B2 IN is connected to C2 OUT, C2 IN is automatically connected to B2 OUT. This approach can in principle be extended to octagon and decagon switches for offices of higher nodal degrees. The current long-haul network, however, is sparse, with an average nodal degree of 2 to 3.

The above approach permits large reductions both in number of switch points and number of switch configurations. Compared to conventional matrix switches, connection-symmetric polygon switches reduce the number of switch points by  $2d^2 / (d(d-1))$ , where  $d$  is the nodal degree (Fig. 3(a)). For a connection-symmetric polygon switch of degree  $d$  with  $n$  wavelength channels (fibers) per degree,

the number of switching states is  $n!$  (for  $d = 2$ ) and  $\frac{(2n)!}{n!} \prod_{i=0}^{n-1} \left( \left( \sum_{j=0}^n \frac{n!}{(2n)!} \left( C_{n-j}^n \right)^2 (n-j)! C_j^n j! \right) - i \right)$

(for  $d = 3$ ). This yields substantial savings compared with the  $(d \cdot n)!$  states of a conventional matrix switch, as shown in Fig. 3(b).

We have designed both a  $16 \times 16$  (8 bi-directional) free-space micromachined matrix switch and a  $12 \times 12$  (6 bi-directional) hexagon switch, both of which were fabricated at MCNC using the MUMPs process [3]. Figure 4 shows their top-view photographs with switch mirrors corresponding to Fig. 2 rotated up. Both switches occupy an area of  $1 \text{ cm} \times 1 \text{ cm}$ . For the hexagon switch, the top switch mirror was omitted due to MUMPs chip-area limits. Figure 5 shows a schematic of the micromachined free-rotating hinged mirrors, whose working principle is described in [2].

The switch described here achieves dramatically reduced loss compared to the  $4 \times 4$  switch without connection-symmetry in Ref. [2]. This results from the use of fiber collimators for coupling, yielding insertion losses of 3.1 dB to 3.5 dB for the shortest and longest front-side paths through the  $8 \times 8$  bi-directional switch (see Table 1). Backside losses, though currently higher (6.3 dB), can be improved via high-reflection backside coating to eliminate polysilicon-plate losses and multiple-reflection effects. Bit-error rate measurements for both mirror sides, shown in Fig.6, show no measurable penalty compared to baseline. It should be noted that the above results were obtained by individually optimizing fiber-to-fiber couplings, and that various nonuniformities in fully packaged devices will tend to enhance loss. Nevertheless, the low losses reported here are regarded as a crucial step towards multi-stage crossconnects that can live within standard cross-office link budgets.

In summary, high-density free-space micromachined polygon switches exploiting network connection symmetry have been proposed and demonstrated. The approach significantly reduces the number of switch points and simplifies the switch configurations. An  $8 \times 8$  bi-directional switch with loss as low as 3.1 ~ 3.5 dB has been experimentally demonstrated, suggesting the feasibility of multistage configurations with very high port count.

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**References:**

- [1] R. W. Tkach, E. L. Goldstein, J. A. Nagel, and J. L. Strand, "Fundamental limits of optical transparency," Optical Fiber Communication Conference, San Jose, Feb. 22-27, 1998.
- [2] L. Y. Lin, E. L. Goldstein, and R. W. Tkach, "Free-space micromachined optical switches with sub-millisecond switching time for large-scale optical crossconnects," OFC'98 and IEEE Photonics Technol. Lett., April, 1998.
- [3] <http://www.mcnc.org>

	PORT 1 → PORT 1 (FRONT SIDE)	PORT 8 → PORT 8 (FRONT SIDE)	PORT 1 → PORT 1 (BACKSIDE)
Loss (dB)	3.1	3.5	6.3

Table 1 Insertion loss of the  $8 \times 8$  bi-directional switch.

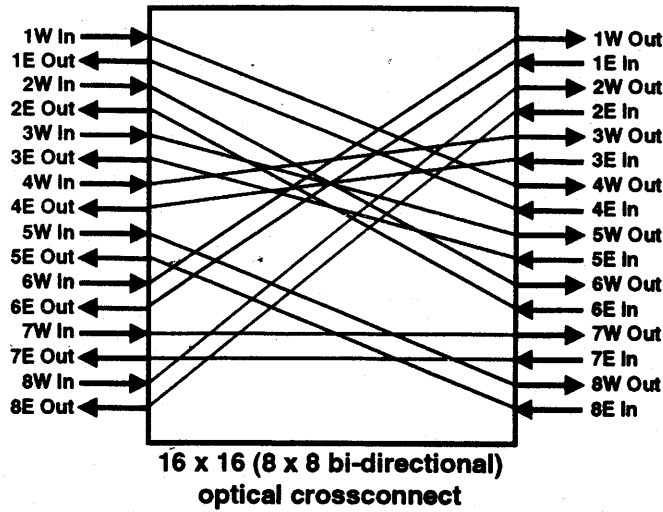


Figure 1 An optical crossconnect supporting symmetric connections.

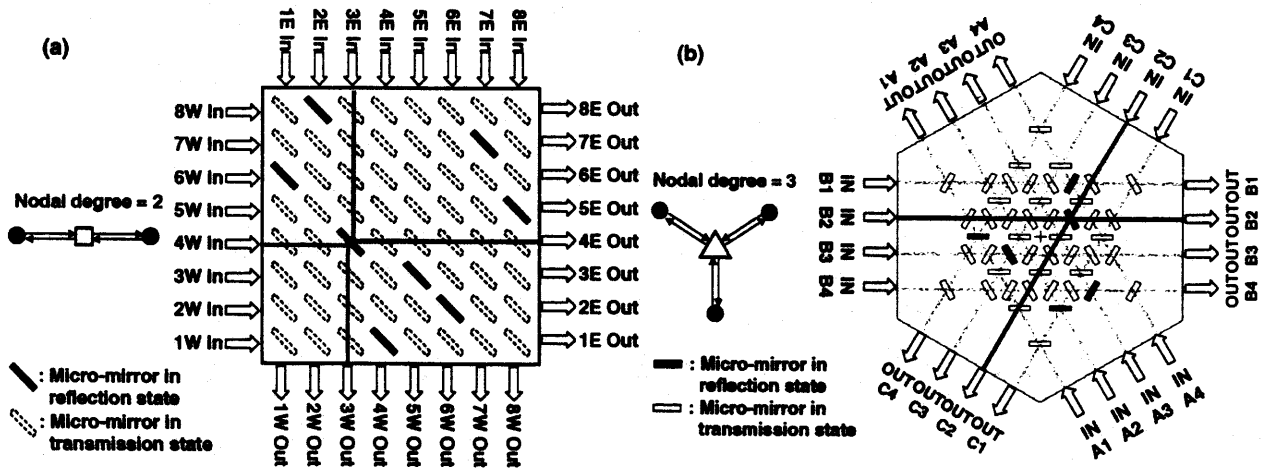


Figure 2 Micro-mirror connection-symmetric switches of matrix (a) and polygon (b) configuration.

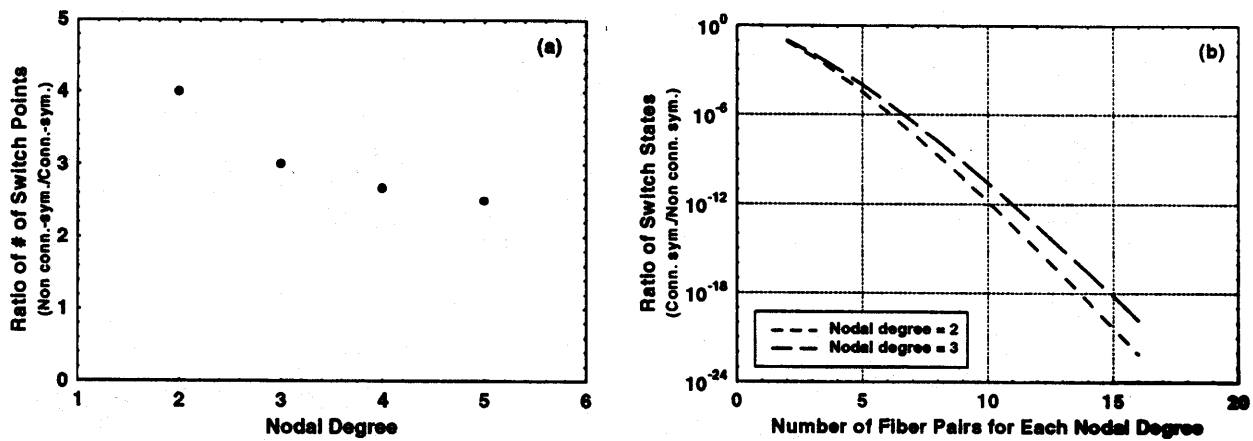


Figure 3 Fractional reduction, via connection-symmetric optical polygon switches, in number of switch points (a), and number of switch states (b).

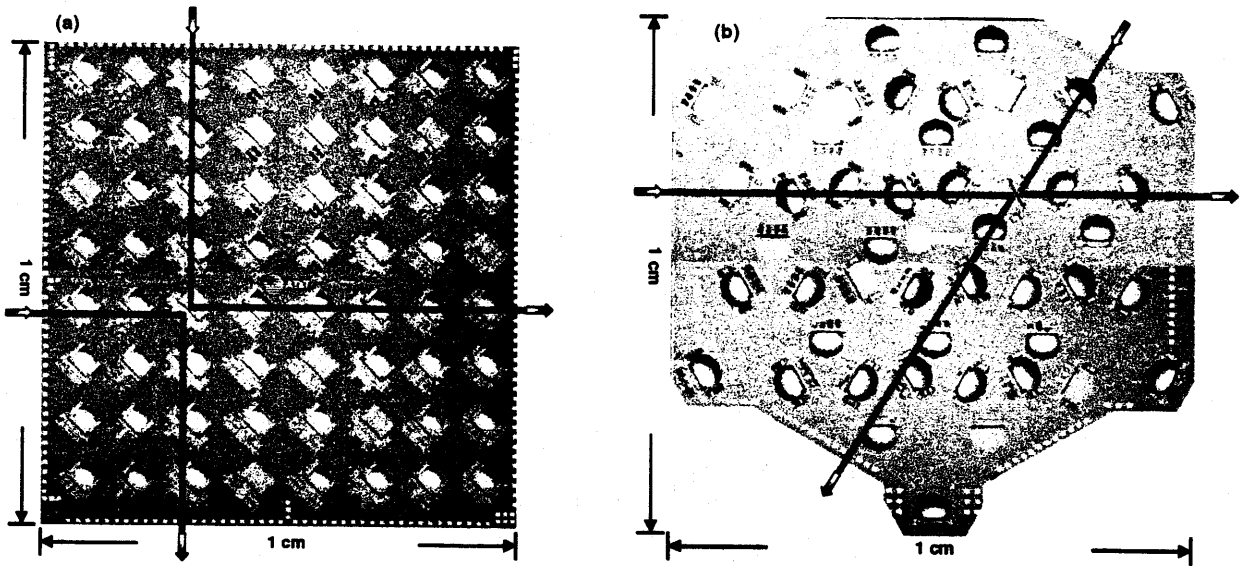


Figure 4 Top-view photographs of free-space micromachined matrix switch (a) and hexagon switch (b) with connection symmetry.

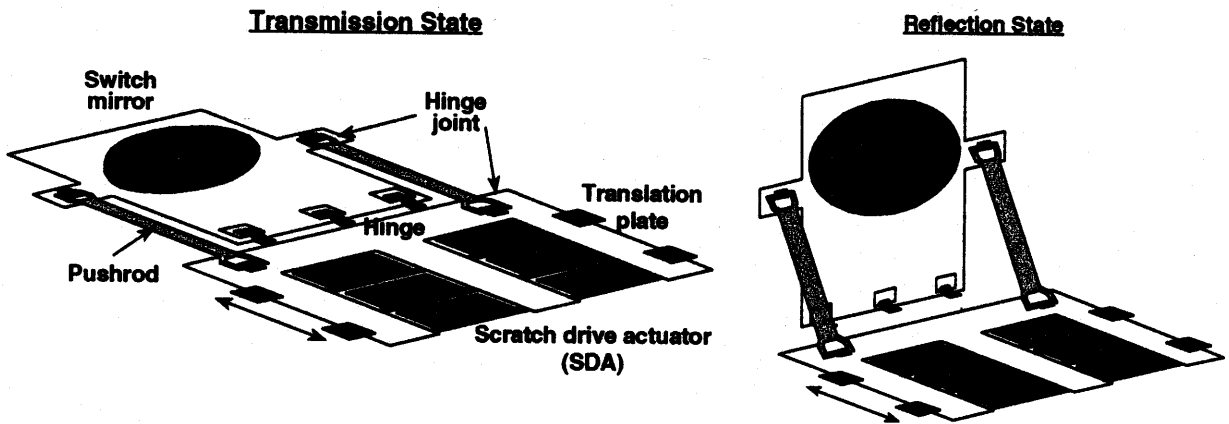


Figure 5 Schematic drawing of the micromachined free-rotating hinged mirror.

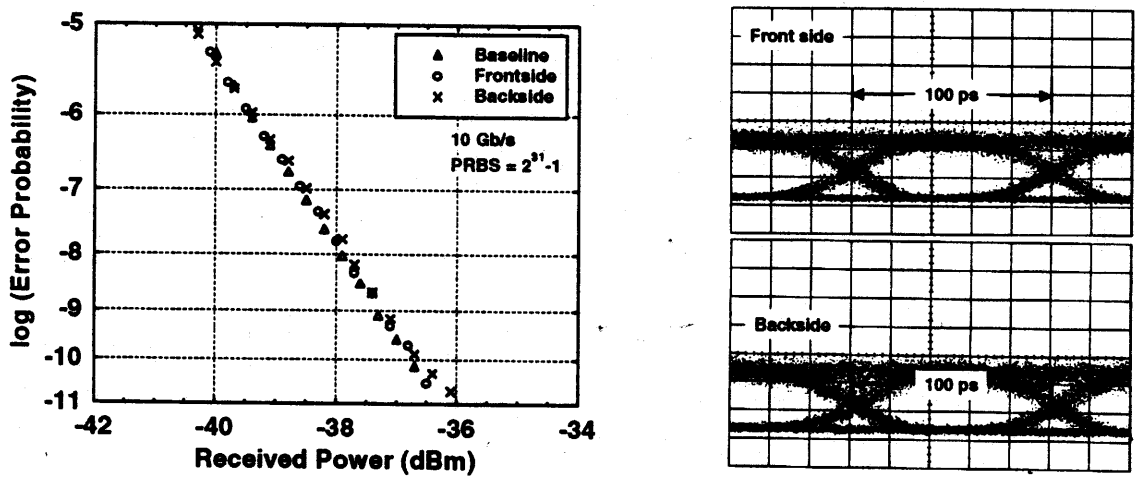


Figure 6 Bit-error-rates and eye diagrams for front- and back-side micro-mirror operation in the bi-directional optical switch. The wavelength used for the measurement is 1.55  $\mu\text{m}$ .