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High-Density Micromachined Polygon Optical Crossconnects Exploiting Network Connection-Symmetry

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Abstract— **Optical-layer crossconnects with high port count appear to be emerging as key elements for provisioning and restoration in future wavelength-division-multiplexed networks. We demonstrate here a means of achieving high-density optical crossconnects utilizing free-space micromachined optical switches that exploit connection-symmetry in core-transport networks. The micromachined polygon switches proposed here are strictly nonblocking. Measured insertion losses of 3.1–3.5 dB for a 16 × 16 (8 × 8 bidirectional) switch suggest the promise of scaling to large port count.**

Index Terms— **Connection-symmetry, free-space, micromachined, optical crossconnect, optical network, optical switch.**

I. INTRODUCTION

OPTICAL-LAYER crossconnects (OXC's) with high port count appear to be emerging as critical elements in future wavelength-division-multiplexing (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 [2]–[5]. Previously, we have demonstrated free-space micromachined optical switches (FS-MOS) which combine the advantages of free-space interconnection and integrated optics [3]. In this letter, we further exploit the connection-symmetry property [6] exhibited by core-transport networks and propose high-density micromachined *polygon* OXC's. The approach significantly reduces the physical size of the switch fabric and simplifies its management. A 16 × 16 (8 × 8 bidirectional) switch with low insertion loss (3.1 ~ 3.5 dB) for nodal degree 2 and a 12 × 12 (6 × 6 bidirectional) hexagon switch for nodal degree 3 on 1 × 1 cm silicon chips have been experimentally demonstrated. The results suggest the practicality of OXC's with far higher port count than previously anticipated.

II. DESIGN AND ANALYSIS

Due to the connection-symmetry inherent in current core-transport networks, OXC's deployed in such networks will also be connection-symmetric. That is, if input A is connected to output B, input B must be connected to output A. This is illustrated in Fig. 1 for an OXC of nodal degree 2, where nodal degree is defined as the number of adjacent offices connected to an OXC. Since all supported connections are bidirectionally 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 as the 4 × 4 device we demonstrated previously [3]. By reflecting signals in symmetric pairs from the two sides of free-rotating micromirrors, symmetric connections can be supported. Fig. 2(a) illustrates this for a matrix switch of nodal degree two; here, the size and complexity of a 16 × 16 switch fabric is essentially reduced to that of an 8 × 8 conventional matrix switch. For higher nodal degree, optical *polygon* switches are required to avoid blocking. The number of required polygon sides is equal to twice the nodal degree. Fig. 2(b) shows an optical hexagon switch with connection symmetry 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. Typical current long-haul networks, however, are sparse, with an average nodal degree of 2–3.

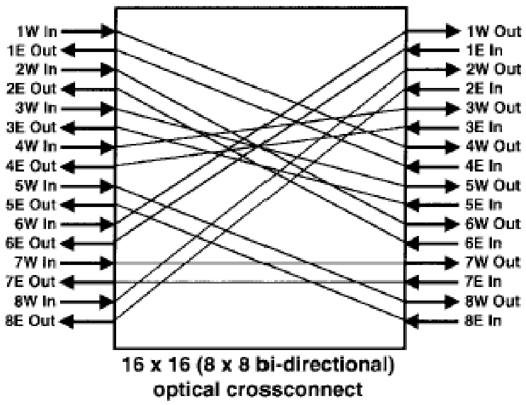

Fig. 1. An optical crossconnect supporting symmetric connections.

The above approach permits large reductions in the number of switch points and therefore the physical size of the switch fabric. Assuming n fiber pairs for each direction, a switching

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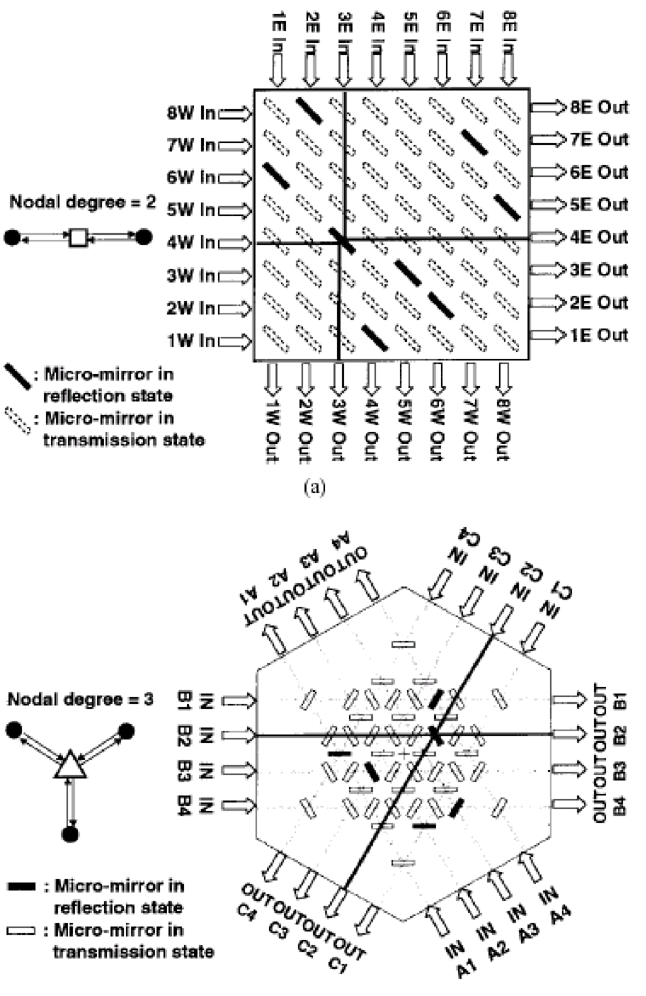

Fig. 2. Connection-symmetric micro-mirror switches of (a) matrix and (b) polygon configuration.

node with nodal degree d has $d \cdot n$ fiber pairs connected to it. For conventional matrix switches without connection symmetry, the number of switch points is equal to $(d \cdot n)^2$. For connection-symmetric polygon switches (including matrix switches) with nodal degree d, the number of switch points required for nonblocking is $[d(d-1)/2]n^2$. Therefore, the ratio of the number of switch points, for a conventional matrix switch compared to a connection-symmetric polygon switch is $2d/(d-1)$. This suggests that significant reductions in switch-fabric size are achievable by exploiting network connection-symmetry in switches of the broad class described here.

III. RESULTS

We have designed both a 16×16 (8×8 bidirectional) free-space micromachined matrix switch and a 12×12 (6×6 bidirectional) hexagon switch, both of which were fabricated at MCNC using the multiuser MEMS processes (MUMP's).[1] Fig. 3 shows the schematic drawing of the connection-symmetric matrix switch. The switch fabric features integration of free-rotating micromachined hinged mirrors on a single silicon wafer. The mirror is built on a polysilicon plate, with 5000-Å-thick Au coating on the plate's front side. The fabrication process and the working principle of the switch mirror have been described in [3]. Submillisecond switching time and very low crosstalk have also been demonstrated. Fig. 4 shows top-view photographs of the connection-symmetric free-space micromachined matrix switch and hexagon switch. The size of the switch mirrors is determined by the fiber collimators used for optical coupling. Switch mirrors corresponding to Fig. 2 have been rotated up. Both switches occupy an area of 1×1 cm. For the hexagon switch, the top switch mirror was omitted due to MUMP's chip-area limits.

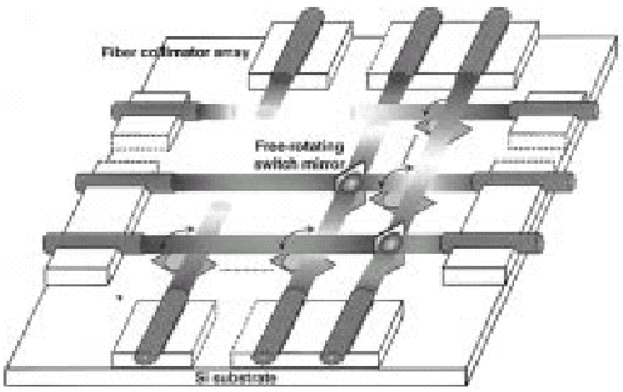

Fig. 3. Schematic drawing of the connection-symmetric free-space micromachined optical switch with matrix configuration.

In the previously demonstrated 4×4 FS-MOS [3], integrated binary-amplitude Fresnel lenses were used for collimating optical beams. This resulted in high, nonuniform insertion loss. In the connection-symmetric FS-MOS described here, fiber collimators are employed for coupling, yielding insertion losses of 3.1–3.5 dB for the shortest and longest front-side paths through the 8×8 bidirectional switch (see Table I). 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 from polysilicon/air and polysilicon/Au interfaces. Bit-error rate measurements for both mirror sides, shown in Fig. 5, show no measurable penalty compared to baseline. Light at 1.55 μm modulated at 10 Gb/s with a pseudorandom bit sequence of $2^{31}-1$ is employed for the bit-error-rate (BER) measurement. 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 increase loss. Nevertheless, the low losses reported here are regarded as a crucial step toward multistage crossconnects that can live within standard cross-office link budgets.

The crosstalk between adjacent channels shows performance similar to the previously demonstrated FS-MOS [3], despite the use of mirror backsides. From one input channel to the output channel located on the opposite side of the mirror, for example, 4W In to 4E Out in Fig. 2(a), there is no measurable crosstalk for the mirror size and gold thickness used here.

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[1] Available: http://www.mcnc.org.

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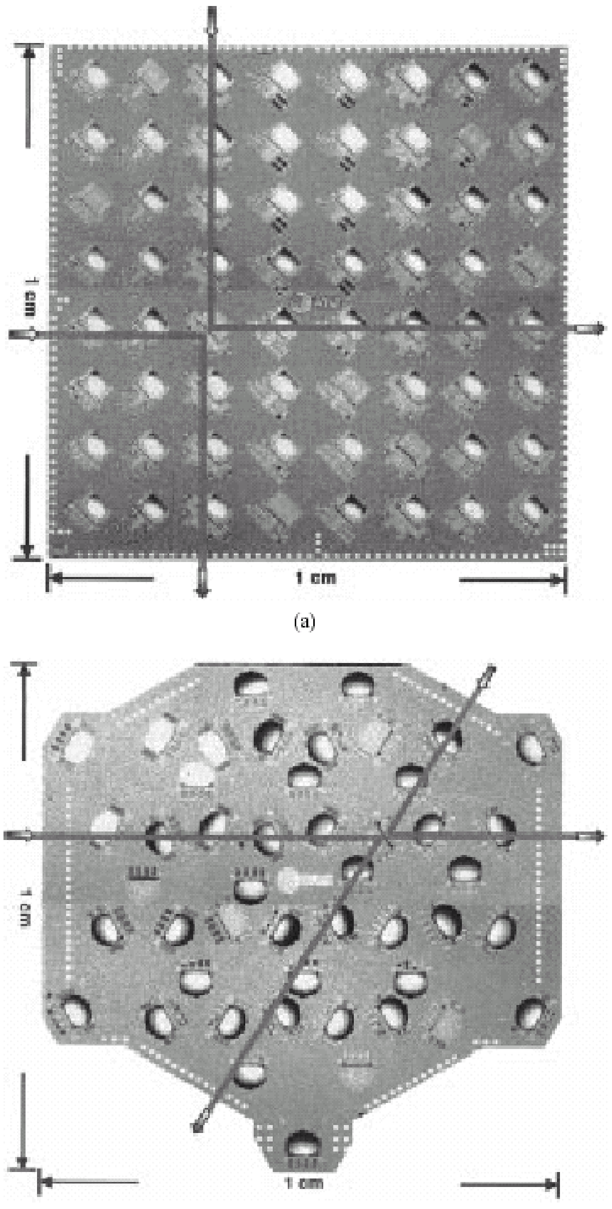


(a)

(b)

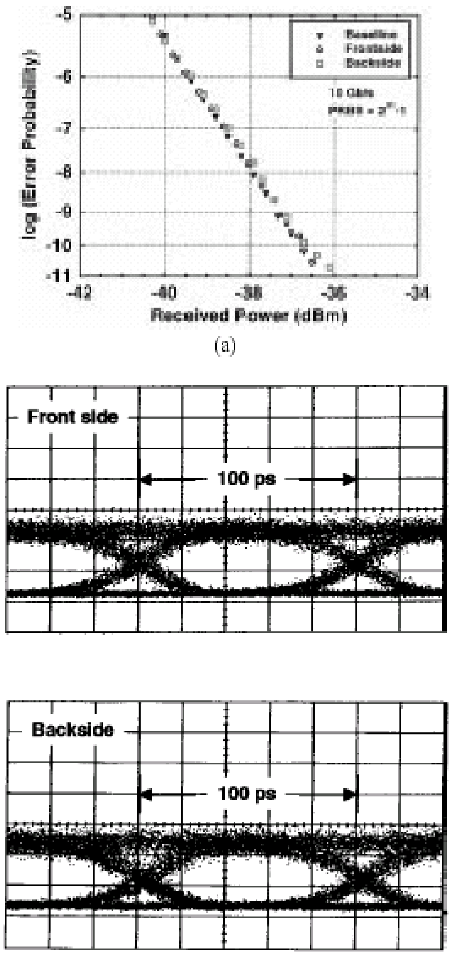
Fig. 4. Top-view photographs of free-space micromachined (a) matrix switch and (b) hexagon switch with connection symmetry.

TABLE I
INSERTION LOSS OF THE 8 × 8 BIDIRECTIONAL SWITCH

	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

IV. CONCLUSION

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 × 8 bidirectional 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.



(a)

(b)

Fig. 5. BER's and eye diagrams for front- and back-side micromirror operation in the bidirectional optical switch. The wavelength used for the measurement is 1.55 μm.

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