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Connection-symmetric Micromachined Polygon Optical Crossconnects for WDM Lightwave Networks

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Abstract

Optical crossconnects are likely to emerge as critical network elements for provisioning and restoration in core WDM networks. The chief physical challenge facing these elements is that of scalability to high port-count. We demonstrate a route to achieving high port count by exploiting connection-symmetry in micromachined polygon switches. Insertion losses as low as 3.1 ~ 3.5 dB for a 16 × 16 (8 bi-directional) switch suggest the promise of scaling to large port count.

Key Words

(060.1810) Couplers, switches, and multiplexers; (060.4250) Networks; (060.2330) Fiber optics communications; (060.2340) Fiber optics components.

Introduction

With multiwavelength transmission technologies poised to swell the information-carrying capacity of an individual fiber by two orders of magnitude, it becomes increasingly important to find new ways to not only transport vast volumes of information, but also to provision and restore it. One promising means of accomplishing this is in core long-haul networks is to build 'opaque' optical-crossconnect-based networks, whose point-to-point transmission links terminate on transponders. This approach arrests accumulating performance-impairments and facilitates fault-location and performance-monitoring. Moreover, the standard interfaces afforded by the transponder make possible both multivendor-interworking and piecewise upgrade of optical transport systems [1]. Taken together, these features offer a promising means, in the near-term, of extracting value from WDM technology not only in the form of enhanced transmission capacity but also in the form of enhanced functionality.

What stands between the above opaque crossconnect-network vision and its implementation is development of the optical crossconnects (OXC) themselves. Since their function is to provision and restore traffic in units of individual wavelengths, whose numbers are in turn rising swiftly with aggregate demand, the chief challenge facing optical crossconnects for this application is clearly 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 × 16 (8 bi-directional) switch with low insertion loss (3.1~3.5 dB) for nodal degree 2 and a 12 × 12 (6 bi-directional) hexagon switch for nodal degree 3 on 1 cm × 1 cm silicon chips have been experimentally demonstrated. The results suggest the practicality of OXCs with far higher port count than previously anticipated.

Design and Analysis

Due to the connection-symmetry inherent in current core-transport networks, OXCs 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.

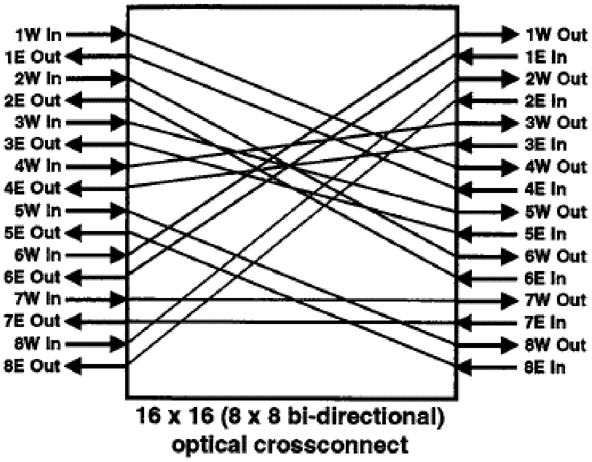


Figure 1 An optical crossconnect supporting symmetric connections.

This is a feature whose substantial lurking economics can be naturally incorporated into a free-space OXC like the 4 × 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 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. Figure 3 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.

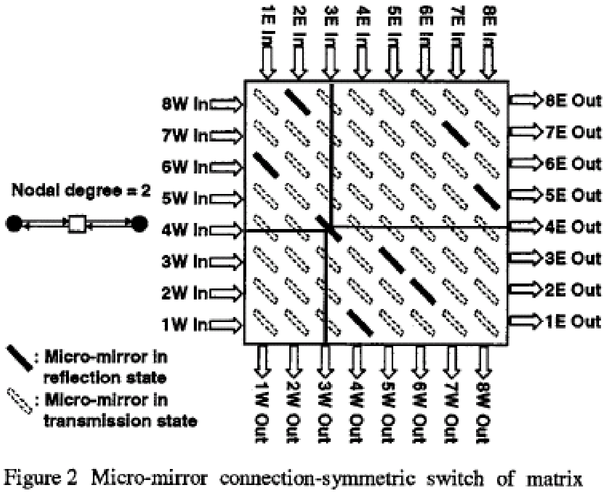


Figure 2 Micro-mirror connection-symmetric switch of matrix configuration.

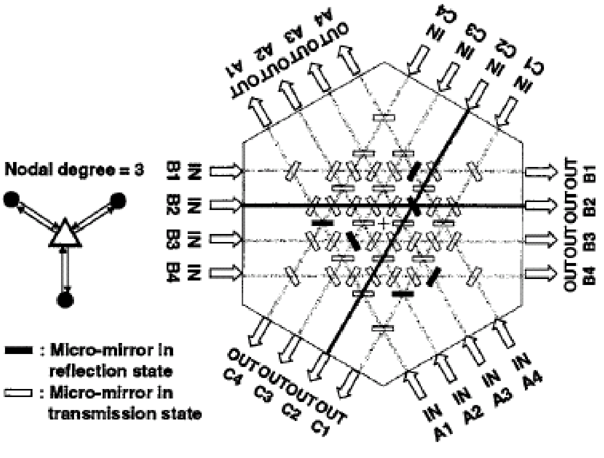


Figure 3 Micro-mirror connection-symmetric switches of polygon configuration.

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 (see Fig. 4).

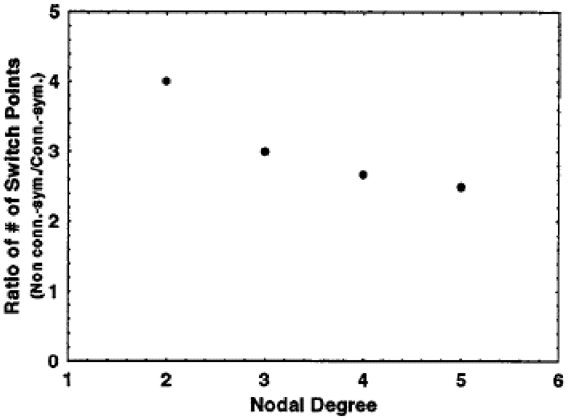


Figure 4 Fractional reduction, via connection-symmetric optical polygon switches, in number of switch points.

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. 5.

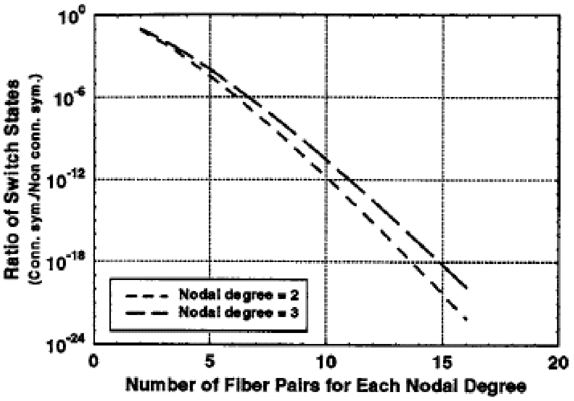


Figure 5 Fractional reduction, via connection-symmetric optical polygon switches, in number of switch states.

Experimental Results

We have designed both a 16 × 16 (8 bi-directional) free-space micromachined matrix switch and a 12 × 12 (6 bi-directional) hexagon switch, both of which were fabricated at MCNC using the MUMPs process [3]. Figure 6 and 7 shows their top-view photographs with switch mirrors corresponding to Fig. 2 and 3 rotated up. Both switches occupy an area of 1 cm × 1 cm. For the hexagon switch, the top switch mirror was omitted due to MUMPs chip-area limits. Figure 8 shows a schematic of the micromachined free-rotating hinged mirrors, whose working principle is described in [2].

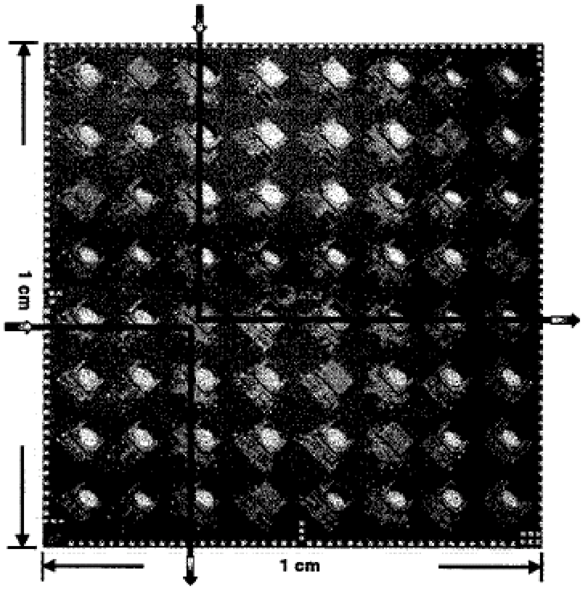


Figure 6 Top-view photographs of free-space micromachined matrix switch with connection symmetry.

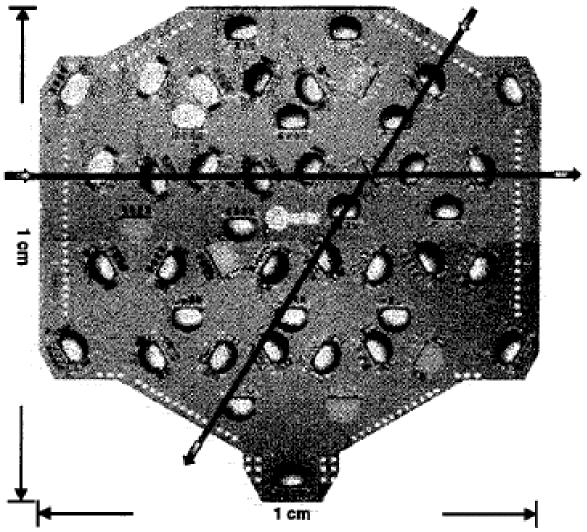
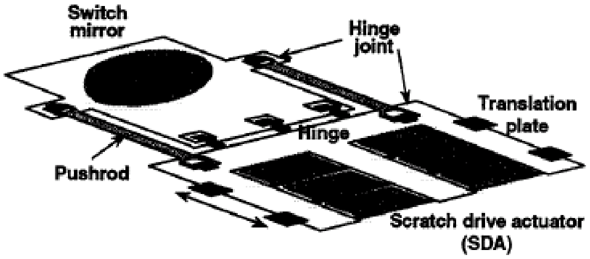


Figure 7 Top-view photographs of free-space micromachined hexagon switch with connection symmetry.

Transmission State



Reflection State

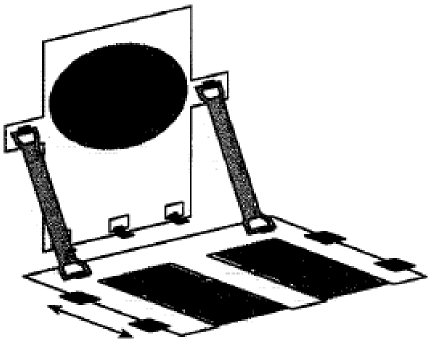


Figure 8 Schematic drawing of the micromachined free-rotating hinged mirror.

The switch described here achieves dramatically reduced loss compared to the 4 × 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 × 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. 9, 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.

Table 1 Insertion loss of the 8 × 8 bi-directional switch.

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

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 dramatically reduces the number of switch configurations, compared with crossconnects that do not exploit connection-symmetry. An 8 × 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 high port count. Such high-port-count crossconnects would then permit one to build opaque WDM networks, thus realizing the aim of extracting from WDM optics not only increased capacity, but also enhanced provisioning and restoration functionality.

Acknowledgment

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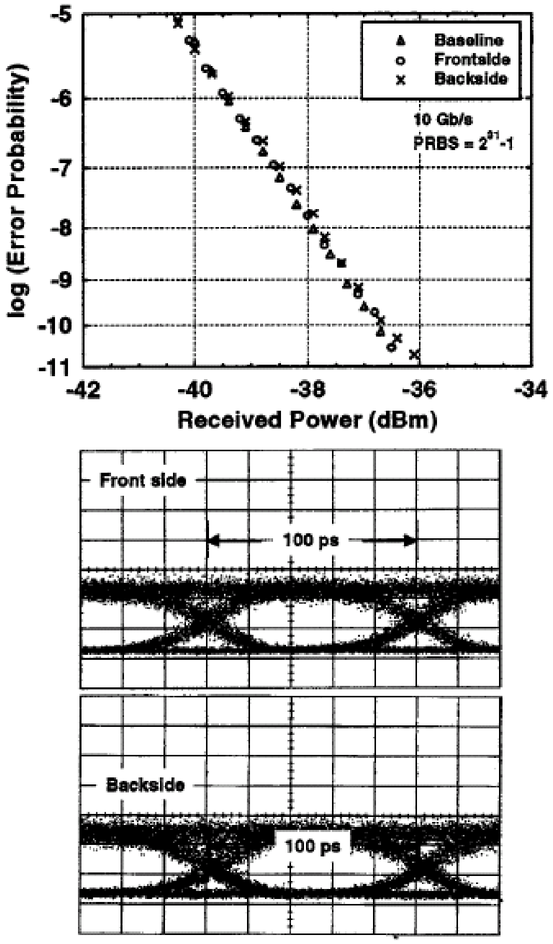

Figure 9 Bit-error-rates and eye diagrams for front- and back-side micro-mirror operation in the bi-directional optical switch. The wavelength used for the measurement is 1.55 μm.

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," IEEE Photonics Technol. Lett., Vol. 10, no. 4, p. 525-527, 1998.

[3] http://www.mcnc.org