

# LARGE SCALE MICRO-OPTIC SWITCHES

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**Abstract:** The rapid growth of video and data transmission is driving the growth of fiber optic transmission and switching. Optical switching is a low power, low cost solution to this need. We review approaches to optical switching and examine the performance that is achievable. We review the interesting aspects of micro-optic design of the fiber collimator array, MEMS mirror deflection and dimensions, and the overall switch performance such as insertion loss, return loss and polarization dependant loss. The testing results from fabricated MEMS based micro-optic switches are compared to theoretical results.

## 1. Introduction

Video and data transmission are growing exponentially, with a doubling time of one year or less[1]. This is driven by widespread broadband and FTTH deployments. The amount of electrical power required to switch this information is growing exponentially and is becoming a significant (>1%) amount of electrical power consumed in many advanced countries[2]. Optical switches are an important solution to this problem because the power required to switch data is typically 1000 times less if high speed electrical switching and OEO conversion are avoided. Fig. 1 illustrates a mesh network utilizing a core of optical switches.

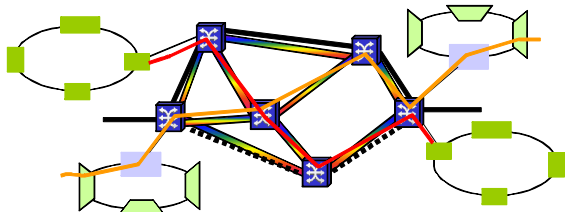


Fig. 1. Illustration of an optical switch core mesh network[3].

Another advantage of using optical switches is the scalability to reconfigurable mesh networks, with the resultant improvement in system reliability and flexibility. The tradeoffs between optical and electrical core switching is illustrated in Fig. 2. Optical switches have a capacity of at least 32 Tbit/s (320 fibers at 100 Gbit/s each) requiring a power of on the order of 1 W, and a size of 0.001 m<sup>3</sup> [4]. This results in capacity/power and capacity/size metrics on the order of 32 Tbit/s/W and 32,000 Tbit/s/m<sup>3</sup>. These are illustrated in Fig. 2, and are 100 to 1000 times better than electrical core switching, but at the expense of switch granularity and switching speed. The important issue is whether the ability to switch packets or subwavelength switch is worth the extra power, weight, size and cost.

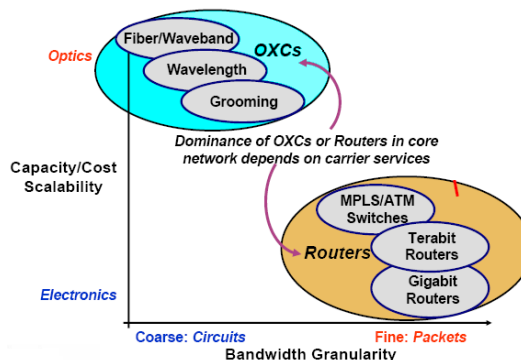


Fig. 2. Tradeoff between capacity and granularity[5].

There are a variety of applications for optical switches in fiber optic networks ranging from fiber switching to waveband switching to wavelength switching. These may be done in a single switch, or in multiple switches, depending on the number of ports required. This architecture is illustrated in Fig. 3. It shows the separation of optical bypass and optical switching from subwavelength switching in the service layer.

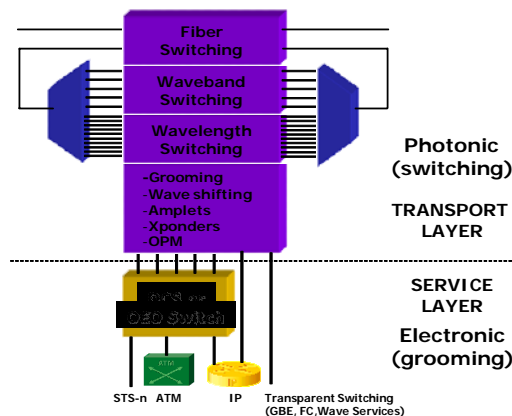


Fig. 3. Separation of transport switching (fiber, waveband and wavelength) from subwavelength service layer switching.

## 2. Optical Switch Scaling

Optical switches tend to scale well as transmission capacity increases due to their transparent switching. This is illustrated in Fig. 4. A switch that was installed to carry 2.5 Gbit/s data can be upgraded to 10 Gbit/s and to multiple wavelengths, resulting in a growth in capacity by three orders of magnitude without expense as the transmission capacity increases and the switching granularity required increases. This does not occur with electrical core switches or routers.

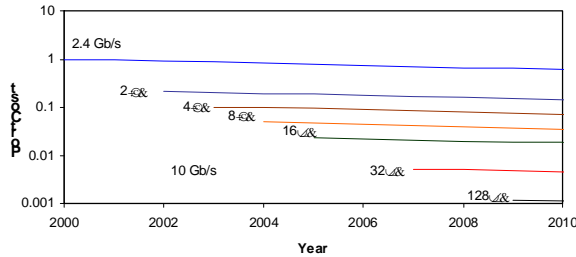


Fig. 4. Relative switch cost as the capacity is increased.

A wide variety of optical switch technologies have been developed, and the tradeoff in speed and switch size is illustrated in Fig. 5. Some technologies are quite fast, with switching times of 1 ns or less, and are important for packet switched systems[6-8]. Many of these utilize passive arrayed waveguide routers with fast wavelength tunable lasers. Other technologies have switching speeds in the microsecond range, and are useful for burst switched networks[9,10]. Microelectromechanical system (MEMS) switches are slower, with switching speeds in the millisecond range.

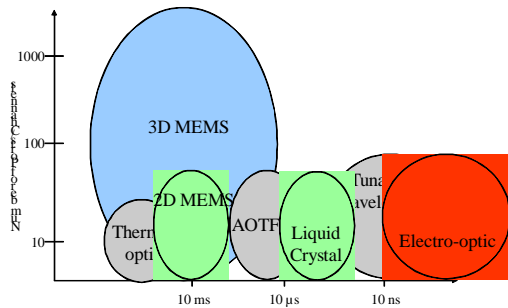


Fig. 5. Comparison of switch technologies in speed and size.

Most of the switch technologies illustrated in Fig. 5 are planar 2D switches. 2D switches are typically composed of 2x2 switches in a crossbar configuration, and so a nonblocking switch requires  $N^2$  switches, as illustrated in Fig. 6. Planar switches are typically 32x32 or less, because of quadratic dependence on port count.

Recently, 3D switches (Fig. 7) have been developed to solve this scaling bottleneck[12-14]. These approaches utilize just  $2N$  switch elements for a nonblocking switch with low loss (Fig. 6). Consequently, large switch arrays of 320 ports and higher have been demonstrated using MEMS technology[12-14]. 3D switches can also be implemented using individual collimators that can be angled to point at each other.

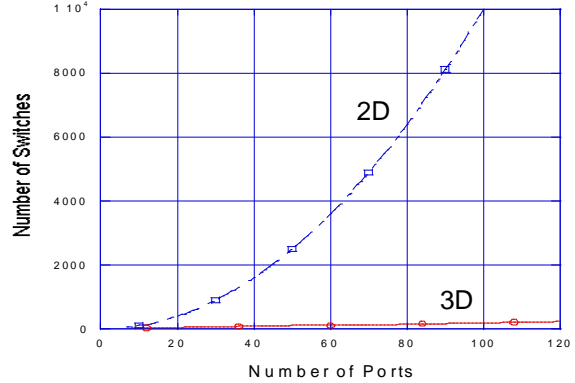


Fig. 6. Comparison of required number of switch elements in 2D and 3D switches.

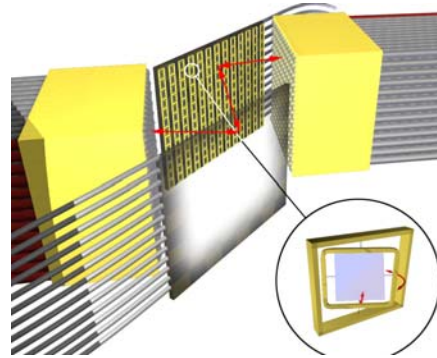


Fig. 7. Schematic diagram of a 3D MEMS switch.

In this remainder of this paper, we will focus on the micro-optic design of large optical 3D MEMS switches. We will present the issues and results of micro-optic design and simulation for a large scale MEMS based micro-optic switch. We also compare our simulation results with the measured results from a fabricated large scale 360x360 MEMS optical switch.

## 2. Optical Design of Large Scale Micro-optic Switches

The key optical design of the large-scale micro-optic switch involves the MEMS mirror size and deflection angle design. The insertion loss of the switching system depends on the fiber collimator array design, the switch size, and the MEMS mirror deflection angles

Diffraction typically dominates the insertion loss. The MEMS mirror can be designed to be large enough so that diffraction effect from MEMS mirror is small; however, larger mirrors result in longer path length, higher vibration sensitivity and tighter mechanical alignment tolerances. A better design is to make the MEMS mirrors to be just large enough such that the clipping or diffraction introduced loss is well controlled.

The fiber collimator array has a fiber array attached to a micro-lens array (Fig. 8). The shape of the micro-lens in

the lens array is spherical. The error of the shape of micro-lens is very important for optical insertion loss. Figure 9 gives the measurement results of a silicon micro-lens shape together with a shape error plot. This figure shows that the rms shape error is 19 nm, which corresponding to a  $0.04 \lambda$  wavefront error for 1550 nm wavelength. Such a small amount of wavefront error will contribute less than 0.4 dB insertion loss.



Fig.8. 400 beam collimator array.

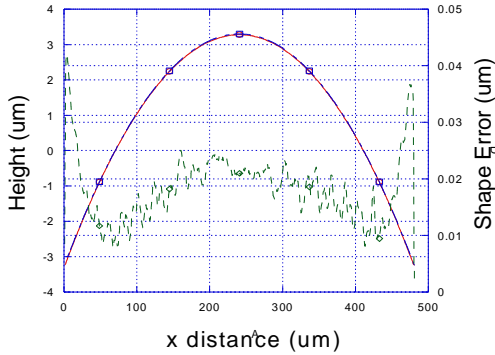


Fig. 9. A typical micro-lens shape (red: design, blue: experimental) and the shape error.

The optical beam pointing error is due to fiber position error, the lens pitch error, and the focal length variations of the micro-lens array. In practice, 98% of the beams have less than 0.5 mrad pointing error.

Figure 10 shows the beam spot size and the beam waist location plot for all the optical beams in a fabricated fiber collimator array at 1550 nm wavelength. The beam waist position error to be within  $\pm 1$  mm, and the spot size error to be  $\pm 15$   $\mu$ m, which are sufficient to achieve a low loss switch.

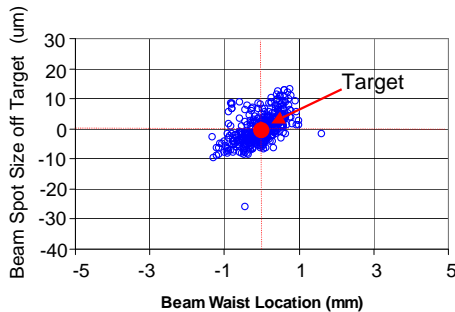


Figure 10. The fiber collimator array beam spot size and beam waist location plot.

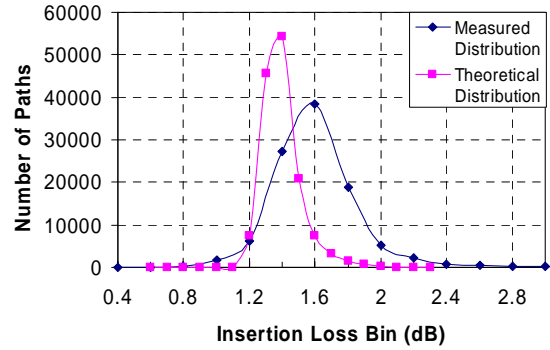


Figure 11. Theoretical insertion loss distribution and the measured insertion loss distribution.

The calculated losses for all 129,600 paths of a 360x360 photonic switch are shown in Fig. 11. The measured losses are slightly higher and have a larger distribution, partly due to connector variation.

Another critical parameter is the return loss. This is dominated by the return loss of the input collimator. A typical distribution is shown in Fig. 12. Some applications require worst case return losses of -55 dB, which has been demonstrated by angling interfaces of the input fiber block.

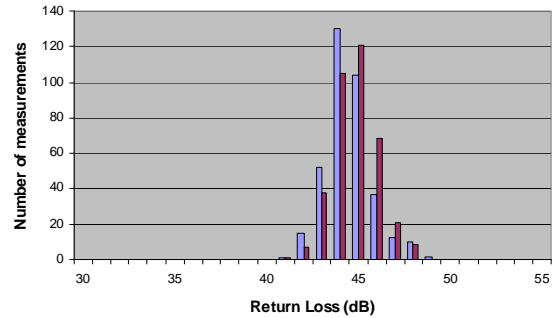


Fig.12. Return loss of a 3D MEMS switch.

The PDL of a switch can also be calculated as part of the switch design. Fig. 13 shows a comparison of measured and experimental PDL distributions of an early switch. Later designs have maximum PDL of 0.2 dB, but the remnant PDL is more random.

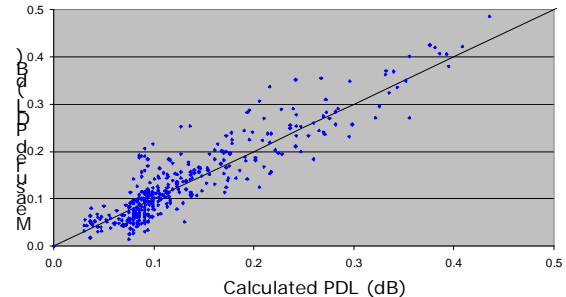


Figure 13. Comparison of measured and calculated PDL of an early switch showing good correlation of calculated and measured PDL.

Other important parameters are directivity, generally less than -70 dB, and crosstalk. Crosstalk is dominated by nearest neighbors. Mirrors farther away have crosstalk contributions below -80 dB. Fig. 14a shows the loss distribution of the desired connection and Fig. 14b shows the crosstalk contributions of nearest neighbors, which are generally below -45 dB.

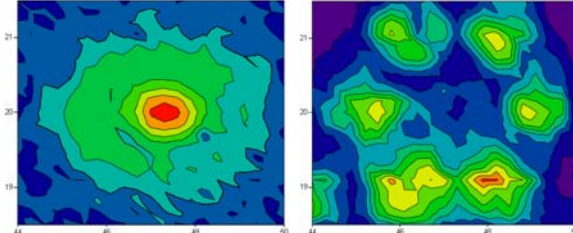


Fig. 14. a) Insertion loss hill in angle space (degrees). Red is 0-10 dB, and each color change corresponds to 10 dB increase, up to 80 dB. b) Crosstalk in angle space (degrees). Red is -40 to -45 dB, and each color change corresponds to 5 dB increase, up to 80 dB.

### Switch Size Scaling

An important issue is scaling switches to larger sizes. Table 1 summarizes how the important design parameters scale with  $N$ , the number of mirrors. Calculations and measurements indicate that performance similar to that shown here should be achievable for 1000x1000 switches. Loss does increase for practical designs larger than 2000x2000.

parameter	symbol	scaling
Beam radius at waist	$w_0$	$N^5$
Beam radius at MEMS mirror	$w_m$	$N^5$
Mirror diameter	$D$	$N^5$
Mirror array area	$A$	$N^2$
Optical path length	$L$	$N$
Active switching volume	$V$	$N^3$

Table 1. Dependence of important design parameters on the number of ports in the switch[15].

### 4. Conclusions

In conclusion, we presented the optical model large scale micro-optic switching using MEMS mirror array. The micro-optic design of fiber collimator array, MEMS mirror deflection, and the overall switch performance such as insertion loss, polarization dependant loss are theoretically simulated and agreed with the testing results from the fabricated 360x360 MEMS based micro-optic switch.

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